NeSS 02

Astrophysical and Cosmological Neutrinos

Working Group

Executive Summary

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Several experimental efforts for the construction of large volume high energy, >1 TeV, neutrino detectors are currently underway worldwide. The main goal of these efforts is the detection of cosmologically distant neutrino sources. Since high-energy neutrino "telescopes" will open a new unexplored window onto the cosmos, their discovery potential is high. In particular, they will allow the investigation of high-energy phenomena in the distant universe. While cosmological sources cannot be observed at photon energies exceeding 100 GeV because of attenuation by γ-γ pair production, high-energy neutrinos will propagate unhindered directly to us from their sources.

The existence of extra-Galactic neutrino sources is implied by the observations of ultra-high energy (UHE), $>10^{19}$ eV, extra-Galactic cosmic rays. The acceleration mechanism of particles to such energy is not understood, and the sources of these extreme energy particles are yet unknown. One of the prime goals of the high energy neutrino telescopes is the identification of the UHE cosmic ray sources. Neutrino telescopes will provide a probe of the most extreme, in the sense of power output and particle acceleration, sources in the universe. Such sources include gamma-ray bursts (GRBs) and active galactic nuclei (AGN), which may be sources of UHE particles. Neutrino observations will provide unique information on the physics of their underlying engines, which is not well understood despite many years of research.

Detection of high energy astrophysical neutrinos could also allow us to study fundamental neutrino-physics issues involving neutrino oscillations and weakly interacting massive particles (WIMPs), to test Lorentz invariance, and to test the weak equivalence principle.

The following main conclusions were reached by the working group:

1. **The observation of cosmic neutrinos above 100 GeV is confirmed to be of great scientific importance. The detection of such neutrinos will open an unexplored window to the most energetic phenomena in the universe.**

2. **Consensus exists that km^3 - scale detectors are required to detect signals from known extra-galactic sources, based on phenomenology and experimental evidence.**

3. **The construction of a km^3 – scale detector is technologically feasible in both ice and water, and the scientific goals can be met with either medium.**

4. **There is a large worldwide community pursuing the development of neutrino telescopes.**

5. **The identification and understanding of point sources is a primary goal of km^3 neutrino telescopes.**

6. **Prospective sources are rare, thus complete coverage of the sky is an important goal; detectors in both the Northern and Southern hemispheres should be built.**

7. **Contemporaneous observations of point-like sources, such as Gamma-Ray Bursters, by neutrino and photon telescopes will allow the identification of the sources and will strongly enhance the prospects for understanding their underlying physics mechanisms.**

8. **>> 1 km^3 volumes are required for the detection of neutrino signals expected beyond 10 PeV. New, emerging techniques such as radio pulse detection in ice or salt provide an opportunity to achieve such large effective volumes.**

9. **The main scientific goals of high energy neutrino observatories are distinct from and generally complementary to those of deep underground laboratories.**

The scientific motivation for construction of high energy neutrino telescopes is discussed in some detail in sec. 1. Operating and planned under ice and water optical Cerenkov detectors are reviewed in sections 2 and

3 respectively. Other detection techniques are discussed in section 4. Additional material can be obtained following the hyperlinks embedded within this document.

1. Scientific motivation

1.1 General considerations

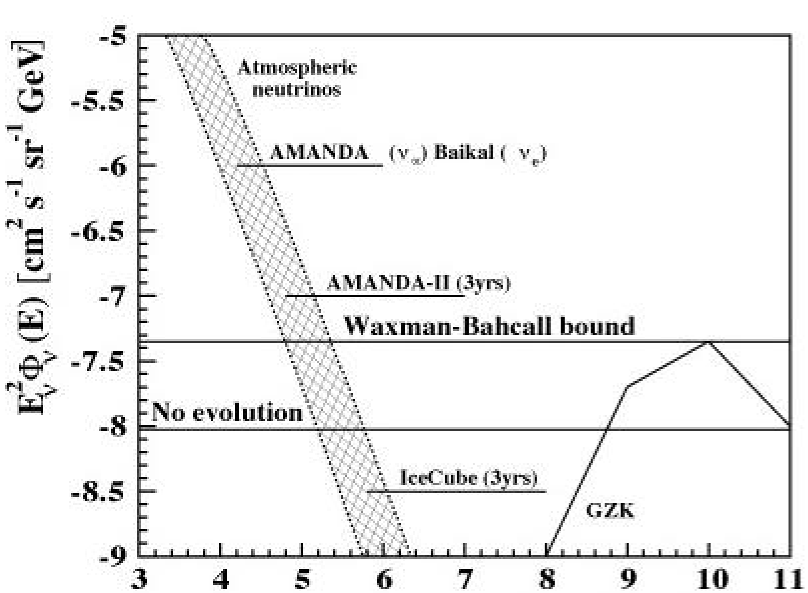
An estimate for the required neutrino telescope size can be obtained by considering the minimum flux of a source that can be detected by a neutrino telescope with effective area A (in the plane perpendicular to the source direction) and exposure time T. The probability that a muon produced by the interaction of a muon neutrino with a nucleon will cross the detector is given by the ratio of the muon and neutrino mean free paths, $P_{\nu\mu} \cong 10^{-4}(\varepsilon_\nu/100\mathrm{TeV})^{\alpha}$ with $\alpha \cong 1$ for $\varepsilon_\nu < 100$ TeV and $\alpha \cong 0.5$ for $\varepsilon_\nu > 100$ TeV. A source with energy flux f_ν in neutrinos of energy ε_ν will produce $N \approx (f_\nu/\varepsilon_\nu)P_{\nu\mu}AT$ events in the detector. Thus, the flux required for the detection of N events is

$$f_n \approx 5\times10^{-12}\,N\left(\frac{e_n}{100\ \mathrm{TeV}}\right)^{1-a}\left(\frac{AT}{\mathrm{km}^2\ \mathrm{yr}}\right)^{-1}\quad \mathrm{erg}/(\mathrm{cm}^2\mathrm{s}).$$

A lower limit to the source flux is also set by the requirement that the signal would exceed the background produced by atmospheric neutrinos. However, for km^3-scale detectors, the atmospheric neutrino background is a less stringent constraint on source flux than the requirement of a detectable signal (except at low energies). For cosmological sources with characteristic distance of $d \sim c/H_0 \approx 4$ Gpc $\approx 10^{28}$ cm, the minimum apparent luminosity for neutrino detection is therefore

$$L_n = 4pd^2 f_n > 10^{46}\ N\left(\frac{d}{10^{28}\ \mathrm{cm}}\right)^2\left(\frac{e_n}{100\ \mathrm{TeV}}\right)^{1-a}\left(\frac{AT}{\mathrm{km}^2\ \mathrm{yr}}\right)^{-1}\quad \mathrm{erg/s}.$$

Objects with observed isotropic luminosities ~ 10^{47} erg/s, which is more than 13 orders of magnitude higher than the Solar luminosity, are rare. The only known persistent sources that produce such high luminosities are AGN. It is therefore clear that km^3-scale neutrino detectors are required for the detection of cosmological sources. This argument holds also for transient sources at cosmological distances. The brightest known transients are GRBs with apparent isotropic luminosities > 10^{52} erg/s lasting over ~ 100 s. Replacing T = 1 yr with T = 100 s in the above equation implies a minimum isotropic luminosity $L_\nu \sim 10^{52}$ erg/s.



The discussion above relates to point source detection. Waxman and Bahcall have shown that cosmic-ray observations set an upper bound to the *diffuse* neutrino flux from sources which, like candidate sources of > 10^{19} eV protons, are optically thin for high-energy nucleons to gamma–proton and proton–proton (neutron) interactions. The upper bound is compared in the figure with current limits for diffuse flux given by the AMANDA-B10 and Lake Baikal telescopes, and the anticipated performance by a 0.1 km^2 detector such as AMANDA-II, which also approximately characterizes the minimum detectable flux by ANTARES and NESTOR. Detectors with instrumented volumes of one cubic kilometer, such as IceCube, provide an improvement in the minimum detectable diffuse flux. However, charm-induced backgrounds may begin to impact the minimum detectable fluxes in such next-generation detectors. Currently, model predictions for charm-induced atmospheric neutrinos vary by orders of magnitude. If sufficiently large, the charm component is expected to become dominant above an energy of 100 TeV. Unfortunately, charm backgrounds will be difficult to differentiate from the diffuse signal because the energy spectra for both sources of events are quite similar. Since the charm-induced backgrounds may rival the signal fluxes uniquely accessible to km^3-scale detectors, and since the relative amount of information carried by a diffuse signal is rather limited without additional spectral or directional information, km^3-scale detectors should rather focus on detection of point-like neutrino sources.

Another important challenge for high-energy neutrino astronomy is the detection of neutrinos produced by UHE cosmic ray interaction with the micro-wave background, marked as GZK in the figure. km^3-scale water or ice detectors are too small to observe the GZK flux. Several new techniques are being developed to observe this UHE flux: radio Cerenkov signals induced in ice may be detectable by ANITA, and the detection of horizontal air showers in the Auger detector may have sensitivity sufficient for the detection of 10^{10} GeV GZK neutrinos.

1.2 Point Sources

Extra-galactic GRBs and AGN plausibly generate UHE cosmic rays, and are therefore likely sources of neutrinos in the TeV to PeV energy range. GRBs are transient flashes of gamma-rays lasting typically for 1 – 100 s, that are observed from sources at cosmological distances. The apparent isotropic luminosities of GRBs are of order 10^{53} erg/s. They are believed to be powered by the rapid accretion of a fraction of a solar mass of matter onto a newly born solar-mass black hole. AGN consist of both persistent and flaring sources with apparent luminosities reaching about 10^{48} erg/s. They are thought to be powered by mass accretion onto 10^6 – 10^9 solar-mass black holes that reside at the centers of galaxies. In both GRBs and AGN, mass accretion is believed to drive a relativistic plasma outflow that results in the acceleration of high-energy particles, which emit non-thermal radiation. A similar process could also power Galactic micro-quasars, which may be considered as a scaled-down version of AGN, powered by stellar-mass black holes or neutron stars.

While models of GRBs, AGN and micro-quasars are successful at explaining the observed phenomena, these models remain largely phenomenological. Major open questions common to all models are (i) Whether or not the relativistic plasma contains protons and nuclei, (ii) To what energy, if at all, are nuclei accelerated in the expanding plasma, (iii) What mechanism accounts for magnetic field generation and electron coupling? In all cases, neutrino observations will provide unique information on the physics of the underlying engine, and may allow to answer the above open questions.

Adopting the standard assumptions of the fireball model of GRBs, which has received support from the verification of the predictions of an afterglow at lower (X-ray, optical, radio) energies, ~10 neutrino induced muon events at 100TeV are expected in a cubic-km detector per year. These events will be correlated in time and direction with GRB gamma-rays, which implies an essentially background free experiment. A larger rate of 1TeV events is predicted if the yet unknown object, the collapse of which leads to the underlying ~1 solar mass black hole “engine”, is a massive star. Thus, neutrino observations will not only shed light on the fireball physics model, which is independent of the nature of the underlying collapsing object, but may also allow to determine the type of collapsing object.

For both AGN and micro-quasars, the dominant energy carrier in the associated jets is at present unknown (with the exception of the jet in SS433, where protons are known to be the carriers). Neutrino telescopes may allow to resolve this question. Detectable fluxes of neutrinos, leading to several events per year above 10 TeV in a cubic-km detector, might be expected from nearby AGN, such as 3C 279 and PKS 0528+134, if the jets contain protons. Several hour outbursts of 1 to 100 TeV neutrinos, leading to several muon events in a cubic-km detector, should precede individual radio flares associated with major ejection events in micro-quasars, if protons carry the jet energy.

The calculation of the neutrino flux from Galactic supernova remnants (SNRs) is straightforward, assuming that a supernova remnant converts significant amount of energy to non-thermal cosmic rays, as expected if SNRs are the origin of Galactic cosmic-rays. The energy flux in ~1TeV muon neutrinos is given by

$$f_n^{SNR} \approx 5\times10^{-12} \left(\frac{n}{1\mathrm{cm}^{-3}}\right)\left(\frac{d}{1\,\mathrm{kpc}}\right)^{-2} \quad \mathrm{erg}/(\mathrm{cm}^2\mathrm{s}).$$

Here, n is the number density of the inter-stellar medium surrounding the SNR. Comparison with our earlier equations shows that several neutrinos could be detected from nearby SNRs for a $\mathrm{km}^3\times\mathrm{yr}$ exposure. Combined with surface arrays, such as IceTop on top of planned IceCube, neutrino telescope will also allow to study the composition of $>10^{15}$ eV Galactic cosmic-rays. Neutrino telescopes will therefore allow to test and constrain theories for the origin of Galactic cosmic-rays.

1.3 Neutrino physics and dark matter detection

Neutrinos are expected to be produced in astrophysical sources via the decay of charged pions. Production of high-energy muon and electron neutrinos with a 2:1 ratio is therefore expected (tau neutrinos may be produced by photo-production of charmed mesons; however, the higher energy threshold and lower cross-section for charmed-meson production, compared to pion production, typically imply that the ratio of charmed-meson to pion production is ~ $1:10^4$). Because of neutrino oscillations, neutrinos that get here are expected to be almost equally distributed between flavors for which the mixing is strong. In fact, if the atmospheric neutrino anomaly has the explanation it is usually given, then one should detect equal numbers of muon and tau neutrinos. Upgoing taus, rather than muons, would be a distinctive signature of such oscillations. It may be possible to distinguish between taus and muons in a km^3-scale detector, since at 1 PeV the tau decay length is ~ 1 km. This will allow a “tau appearance experiment”.

Detection of neutrinos from GRBs could be used to test the simultaneity of neutrino and photon arrival to an accuracy of ~ 1 s (~ 1 ms for short bursts), checking the assumption of special relativity that photons and neutrinos have the same limiting speed. (The time delay due to the neutrino mass is negligible: for a neutrino of energy ~ 1 TeV with mass ~ 1 eV traveling 1 Gpc the delay is ~ 0.1 m s.) These observations would also test the weak equivalence principle, according to which photons and neutrinos should suffer the same time delay as they pass through a gravitational potential. With 1 s accuracy, a burst at a distance of 1 Gpc would reveal a fractional difference in limiting speed ~ 10^{-17}, and a fractional difference in gravitational time delay of order 10^{-6} (considering the Galactic potential alone). Previous applications of these ideas to supernova 1987A, where simultaneity could be checked only to an accuracy of order several hours, yielded much weaker upper limits: of order 10^{-8} and 10^{-2} for fractional differences in the limiting speed and time delay, respectively.

Weakly Interacting Massive Particles (WIMPs) are possible constituents of the cold dark matter. If WIMPS populate the halo of our galaxy, the Sun or Earth would capture them where they would annihilate occasionally into high-energy neutrinos. The rate depends on the details of the model. A widely discussed WIMP candidate is the lightest neutralino in minimal supersymmetric models. High-energy neutrino telescopes complement direct search detectors by reaching good sensitivity at high neutralino masses, typically in excess of a few hundred GeV, and by allowing us to probe regions of parameter space with large branching fractions to W and Z bosons. Neutrino telescopes currently under construction, with ~ 0.1 km^3 effective volumes, are expected to probe fluxes that are ultimately constrained by the intrinsic background from atmospheric neutrinos. IceCube will provide nearly an order of magnitude improvement, and will probe parametric regions complementary to direct detection methods

2. Ice Detectors

2.1 AMANDA

AMANDA is located at the Amundsen-Scott Research Station located at the geographical south pole. It uses the deep transparent ice of the ~3 km thick polar cap to detect optical Cerenkov radiation induced by muons or electromagnetic showers. The array of 19 strings has a total of 667 optical modules (OM). The outer nine strings are deployed around a circle of 200 m radius, and reach depths of from 1150 to 2350 m. The array was deployed using a hot water drilling technique during austral summers over a period of seven years, from 1994 to 2001. Analog signal transmission from the OM was employed first over copper wires, offering simplicity but introducing substantial signal distortion. Later strings added analog transmission via optical fibers, which offer reduced dispersion, but which displayed unpredictable losses during the "freeze-back" period, just after deployment.

The optical properties of the deep ice have been determined by a combination of *in situ* devices such as lasers, blue/UV LED beacons, and DC light sources. The copious down-going muon event sample has provided an additional calibration source . The extremely low radioactivity of the ice provides an essentially background-free detection medium (~500 Hz per OM). The extracted optical properties include the expected (and found) presence of dust layers, an effective scattering length (~22m), and a very long absorption length (~100m); collectively, these optical characteristics offer both advantages and complications in the reconstruction of events, and are not expected to compromise scientific reach. Upward-going muons are observed at the rate expected from atmospheric neutrinos, cleanly differentiated from the downward CR muon flux.

AMANDA has proven the viability of the basic hot-water drill deployment concept, has confirmed that the low-temperature ice is a suitable environment for operation of optical modules with active electronics, and has demonstrated routine operation of a large array at a site inaccessible for most of the year. It has demonstrated that the ice is a suitable medium for effective study of high-energy neutrino sources. One of the strings in AMANDA was constructed as a "hybrid", with both analog signal transmission and an innovative signal capture/digitization technical approach embedded in the OMs, to permit a transition to an all-digital architecture appropriate for the km-scale project IceCube.

2.2 IceCube

IceCube builds on the broadly successful experience of AMANDA to reach a 1 km scale in all three dimensions. The array will consist of 80 strings, with 60 OMs per string, spaced at ~125 m in an approximately hexagonal geometry. The two major differences from AMANDA are in data acquisition, and in the presence of an air-shower array – IceTop - at the surface. IceCube will be sensitive to neutrino energies from ~10^{11} eV to >10^{16} eV in the upward-going direction, and even higher energies may be detected cleanly in the downward-going hemisphere, as CR backgrounds rapidly become negligible beyond 10^{16} eV. The km scale of IceCube provides excellent pointing resolution in all directions, limited predominantly by physical processes inherent in the neutrino-nucleus interaction. Sensitivity to neutrinos from supernova events (E_ν ~10^7 eV) within our galaxy, perhaps even to the LMC, is facilitated by the complete absence of radioactive backgrounds in the ice.

The transition to a decentralized digital data "network" provides dispersion-free, nearly dead-timeless, high dynamic range waveform capture, thereby optimizing data quality. The digital approach is also expected to increase reliability, reduce costs for construction and operation, minimize pole-based personnel, and simplify deployment and commissioning. The excellent performance observed with the hybrid string in AMANDA provides confidence that the all-digital technology is both a powerful and prudent choice. An enhanced hot-water drill is being constructed to enable the deployment of 16 strings per season.

IceTop will place additional detectors near the surface location of each string. Air showers generating muons within IceCube can be tagged, permitting an experimental verification of background rejection and energy calibration. Perhaps most importantly, this unique combination of both surface and deep detector permits penetrating air showers to be studied for both nuclear composition and possible exotic effects present in the penetrating muonic component.

Deployment should require five to six years, and is expected to start in 2004. Recovery of equipment, once deployed, is of course impossible, and attention is therefore focused on high-reliability methodology. In this regard, the low temperature of the ice is highly beneficial for electronics.

3. Water Detectors

Water Cherenkov detectors for astrophysical neutrino detection were perhaps first suggested in 1960 by Markov and, independently, by Greisen, who envisaged a sphere perhaps 15 m in diameter. Major discoveries in the study of solar and atmospheric neutrino flavor oscillation have been made with detectors based on this idea. For the study of higher energies, US-led DUMAND began the deep ocean exploitation, but was prematurely terminated due to technical problems. Outside the US, activity has been focused on the deep Siberian Lake Baikal and the Mediterranean Sea. The optical properties in lake and sea are quite different from ice, typically reversing the impacts of scattering and absorption. Reconstructed pointing accuracy is expected to be somewhat better than in ice at the highest energies due to the relatively low optical scattering in seawater. Background noise in seawater is roughly two orders of magnitude higher due to the presence of ^{40}K and bioluminescence. Sedimentation at some sites will prevent upward- facing OMs. All ocean-based detector concepts employ some kind of flexible tower structure, anchored to the sea floor, with buoyancy added to the upper layers to strive for verticality. In all cases, recovery of equipment for repair in the event of a malfunction is planned.

There are several independent efforts for the development of a neutrino observatory in the Mediterranean sea. The HENAP committee has recognized the value of independent technology development and testing for the construction of a 0.1 km^3 detector, but has strongly encouraged the coalescence to a single unified effort for the approach to a 1 km^3 detector.

3.1 Baikal

Spanning nearly two decades of effort, this Russian-German collaboration has succeeded in bringing NT-200 into operation in 1998. This array consists of eight strings with a total of 192 OMs suspended from an umbrella-like structure at a depth of ~1 km. The effective area is on the scale of 0.01 km^2. The OMs are operated in a tight pair-wise coincidence to reduce the impact of bio- and chemi-luminescence. In 1993, NT-36, the first continuously operating under-water high energy neutrino detector, was realized. NT-36 reported the first neutrino candidate events during 1994-1996. While Baikal could be considered for km-scale development, the rather shallow depth places this site at a disadvantage.

3.2 ANTARES

This French-led collaboration will deploy an array consisting of ten strings off the southern coast of France near Toulon at a depth of ~2400 m. The string geometry resembles DUMAND, except that a triplet of OMs clustered at a given position offers the possibility of rejecting background noise through local coincidence. The project initially intends to transmit all data through optical fibers to the shore for trigger processing. Undersea connection of the towers to the shore cable will be managed by ROVs. Advances in undersea technology developed for oil-industry purposes provide confidence that the difficulties encountered earlier by DUMAND will be absent. The array is scheduled to be fully deployed by 2004 – 2005 and should achieve a 0.1km^3 effective volume. Experience gained will provide the basis for an extension to 1 km^3-scale, possibly in concert with the NEMO collaboration.

3.3 NEMO

The NEMO collaboration aims at a full 1 km^3-scale detector. The NEMO site is ~80 km from the east shore of Sicily, at a depth of 3500 m. Towers will be constructed of 20 m long horizontal beams with two OMs at each end. Each story is perpendicular to those just above and below; four mechanical cables between each story control spacing and provide torsional rigidity. Sixteen stories, each spaced by 40 m, will provide a total active tower height of 600 m. The design is strongly influenced by the need to optimize the deployment and recovery procedures. Interconnections between towers and the shore cable will be made by ROV. The first NEMO tower is scheduled for deployment in a test site near Catania in 2004. The NEMO collaboration intends to choose a final site and deployment technology in concert with the ANTARES group once experience with operating the ANTARES strings is mature. NEMO is at present a predominantly Italian collaboration.

3.4 NESTOR

The NESTOR site is near Pylos, on the Greek Peloponnesus, and only 15 km from shore. At 4100 m, NESTOR is the deepest of the considered sites. Somewhat further out, the depth reaches 5200 m. The greater depth reduces CR muon background to the practical minimum, and also permits a larger sensitive angular range near the horizontal. The measured optical properties at depth are the best known in the Mediterranean Sea. Towers are built of hexagonally-shaped titanium floors of 32 m diameter. Two OMs are placed on each of the six vertices of a floor, with one OM looking upward, the other downward. Signal processing occurs inside a central sphere for each floor, where real-time coincidence logic reduces background noise by several orders of magnitude.

NESTOR will avoid the use of ROVs, or any need to make at-depth connections. An innovative triangle-shaped sea-going deployment platform (51 m side length) permits each floor to be positioned underneath, with connections made dry. Each tower is sequentially constructed at the site and lowered to depth when complete. Tests of single floors have included successful operation of a fully instrumented floor, with digitizing electronics, in the bay of Navarino, at Pylos. Deployment of a three- or four-floor array for initial physics operation at the NESTOR site is scheduled for 2003.

4. Other Techniques

To probe the energy domain above 10^{17} eV, where the effective volume required for the detection of expected signals exceeds the $1km^3$ scale of planned optical Cerenkov detectors such as IceCube, other disparate approaches are under active development. Directionality information is possible in some cases, others would provide mainly an energy signature.

4.1 Radio Signals

Askaryan has discussed electromagnetic shower development in condensed matter, noting that a naturally occurring charge imbalance will lead to the generation of a radiated Cerenkov pulse, in the GHz range. The radiated signal energy rises quadratically with shower energy, limiting application of this technique to the highest energies of interest. The phenomenon has been demonstrated in laboratory experiments. Attenuation lengths of these pulses in ice and in naturally occurring salt deposits may be as much as an order of magnitude larger than the characteristic attenuation lengths of optical signals in ice/water. This circumstance suggests that very large volumes of ice, salt, or even rock, may offer the opportunity to extend the search for neutrinos above 10^{17} eV with extremely sparse instrumentation. The RICE project uses an array of antennas in the south-pole to examine the possibility of constructing a $>>1km^3$ detector for UHE neutrinos. Using the Goldstone Array to observe the moon's regolith, the GLUE experiment has placed limits on fluxes above 10^{19} eV. One innovative new experimental entry in this arena is ANITA, which will employ a balloon payload with sensitive radio pulse receivers to search for such signals emanating from the Antarctic icecap. ANITA is approved for construction, and is scheduled for flight in 2005.

The Askaryan effect will produce similar signals in salt domes of sufficient dryness. In this case, holes drilled into the salt to permit placement of receivers would be necessary. Hundreds of potential sites exist in the US.

4.2 Horizontal Air Showers

Now under construction in Argentina, the Auger Observatory will instrument an area of roughly 3000 km^2 with small water tank Cerenkov detectors. While primarily intended to study downward-going air showers, the array will also have sensitivity to air showers developing horizontally. Such showers can only be created by UHE neutrinos entering the atmosphere at a grazing angle. All other CR components will be strongly absorbed prior to reaching the Auger detectors due to the very large attenuation along a horizontal path through the atmosphere. While the angular acceptance is small, the large sensitive area of the Auger array leads to a capability that is comparable to the balloon radio technique at energies $>10^{19}$ eV.

On a longer time-scale, space-based telescopes (EUSO, OWL) are considered, which may allow to measure the air fluorescence induced by $>10^{19}$ eV air showers over a circular patch of the atmosphere as large as 3000 km in diameter.

4.3 Acoustic Signals

The development of an electromagnetic or hadronic shower is known to create a short burst of acoustic energy, due to localized thermal expansion. The attenuation length of such signals in the ocean is expected to be more than an order of magnitude greater than the corresponding Cerenkov optical attenuation length. The possibility of detecting neutrino-induced signals in the ocean has been apparent for a long time, and the characteristic signature of this pulse is well understood. However, background noise in the ocean is a limiting factor, as are the technical challenges associated with the deployment of a widely dispersed array of hydrophones appropriate for signal capture and event reconstruction. The energy threshold depends on the presumed array characteristics, but is likely to be in the GZK regime of 10^{19} eV and above. Some effort is underway to exploit existing arrays originally intended for military surveillance, but this effort may lag behind the other techniques noted above. It should be noted that this approach, while not discussed at NeSS02 due to lack of time, may eventually be fruitful.

NeSS E&O Working Group Summary Report

Education and Outreach E&O Working Group

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The E&O Working Group was charged with the task of assessing and envisioning the E&O opportunities associated with neutrino and subterranean science. The Working Group participants included "E&O liaisons" from each of the other Working Groups and other individuals recommended by the Working Group Leaders. The participants already are engaged in significant E&O efforts associated with NeSS, and have the vision and energy to make these efforts even more effective. Many participants gave talks describing a key E&O activity. The E&O Liaisons gathered information and ideas from their science groups and presented these to the E&O group. Short biographical statements of participants, plus abstracts and [need link here] complete versions of these talks are available on line.

Based on the themes that emerged from these talks, extensive group discussion, and other relevant documents provided by the participants, we envision that NeSS E&O will:

> *Develop and foster an arena of accessible resources, including opportunities and information, in which educators, students, and the public can experience working science facilities in ways that further their knowledge about, understanding of, and attitudes toward science and technology.*

The members of the E&O Working Group believe that, were we forced to function in the "add-on" conditions under which the vast majority of E&O programs are planned and funded, it would not be possible to achieve this ambitious vision. Operating under "add-on" conditions entails serious constraints that often result in E&O programs that:

- are unfocused and uncoordinated in their goals and program strategies;
- cannot offer the sustained programming that fosters faculty and teacher investment;
- operate with little if any of the benefits provided by evaluation and benchmarking;
- are unable to address key workforce issues; and
- generally are not able to optimize the use of scientists' and teachers' time and effort.

However, we believe that we will be able to realize our vision because NeSS E&O programs are being planned not as an "add-on," but from the ground up—as an integral part of the proposed and existing NeSS facilities. These facilities are especially promising for E&O programs due to the following five factors:

1. Ground-up coordinated context: NeSS E&O activities will occur within a "built in from the beginning" context. This context will enable an integrated set of projects to be:

- selected in order to realize a well-defined set of goals (including the key goal of diversifying and developing the national science workforce);
- located in appropriately designed and resourced environments;
- of sufficient duration to engage the commitment of scientists, teachers and other key constituents; and
- implemented efficiently by trained staff who will:
  - connect proposed and existing program elements and systematically build on existing infrastructure,

- design programs that effectively foster understanding of the process of science and are aligned with state and national science standards, and
- seek to maximize human and other resources in light of evaluation findings and lessons learned from similar activities nationally.

Our E&O programs will provide immersion-based professional development in science for *pre-college educators* in hands-on, inquiry-based, learn-by-doing ways. Training in teaching methods and pedagogies for *college educators, scientists, graduate students, and post-docs* also will be an important part of the collaborative science and education endeavor. Research opportunities will be provided for *undergraduate college educators* who normally are not afforded the resources to conduct research through their home institutions. The NeSS facilities will offer ongoing opportunities for educators and *undergraduate students* to participate in and generate research experiments in collaboration with the facility-based scientists or in independent settings.

2. Fundamental origins questions pursued in remote and extreme frontier environments: Able to exploit the excitement of pursuing fundamental questions in remote and extreme venues, the NeSS E&O programs promise to be unusually compelling and "contagious" for teachers, students, and the public. Outreach will not only inform the public about the science that is happening but also excite individuals about the potential for discovery in these frontier environments.

3. Cutting-edge multidisciplinary science: The cutting-edge multidisciplinary nature of the NeSS facilities affords their E&O offices unparalleled opportunities to develop high quality programs that build on the resources of several disciplinary communities and that open exciting opportunities "at the intersection of disciplines" for students and scientists as well as K-12 teachers.

4. Collaborative multi-site effort: The E&O activities will be developed and implemented in ways that draw from the resources of the multiple NeSS sites, avoid redundancy and achieve synergy and, in turn, strengthen the already emerging inter-institutional and inter-facility collaborations among NeSS scientists.

5. Facilities located in areas inhabited by underserved populations: The location of the NeSS facilities affords us the opportunity to work especially hard on understanding and meeting the needs of under-targeted, underserved groups—rural people, and Native Americans. Moreover, the network among NeSS facilities will provide access to effective professional development to teachers in rural, urban, and/or suburban areas and teachers in districts with high minority enrollment. Thus, we can work in a sustained and strategic manner to meet the need to increase the proportion of U.S.-born youth, especially those from under-represented groups, in the science workforce.

Overall, with these scaffolds in place, the ability to communicate to teachers and the public the excitement and process of science becomes reality. This approach facilitates the connection of cutting-edge science with education by optimizing the use of limited education and outreach resources.

Recommendations

Given the opportunities afforded by the NeSS facilities we offer the following recommendations.

With regard to *organization and infrastructure*, we propose that:

- NeSS E&O use a "coordinated semi-independent projects" organizational model, and use an "E&O Projects Advisory Committee" (PAC) to review the education and outreach components of all experiments proposed for NeSS, much like PACs already operate in reviewing science proposals at national labs;
- E&O staff work with NeSS scientists to provide resources in the development of experiment-led E&O opportunities;
- the E&O offices include staff who are familiar with the research literature about how to optimize the use of scientists' time in E&O activities; and
- the E&O activities are integrated into the budget structure of the facilities in a manner that ensures long-term funding and sustainability.

With regard to *overall guiding principles* for developing E&O programs, we propose that the E&O programs:

- develop a sustained teacher-scientist network;
- build onto the infrastructure of existing E&O programs, such as TEA, Quarknet, the Timbuktu Academy, and so forth;
- utilize "bottom-up/top-down" strategies that introduce scientist to issues of education while at the same time introducing educators to science processes and content;
- maximize the effective transfer of knowledge though interactions of "near peer" groups (e.g., graduate to undergraduate students);
- match the strengths and talents of individual scientists to the interests of various audiences;
- seek input and support from community leaders, where appropriate, and particularly from ethnic minority groups in geographic areas near NeSS facilities; and.
- encourage university administrators to support and reward faculty who engage in E&O activities.

Executive Summary
Neutrinoless Double Beta Decay

Summary statements

1. Neutrinoless double beta decay is our most promising technique for determining the overall scale of neutrino mass. Recent neutrino oscillation results provide compelling arguments for new experiments with 100-fold increases in sensitivity.

2. Several promising experiments using distinct technologies have reached an advanced stage of development. Because the ultimate sensitivity of new techniques is difficult to anticipate, more than one next-generation experiment must be supported.

Summary

Recent oscillation results have determined neutrino mass differences, but not the overall scale of neutrino mass crucial to both particle physics and cosmology. While next generation tritium endpoint experiments may be able to probe masses of about 0.3 eV, neutrinoless double beta decay is the only tool for reaching 0.01 eV, the level suggested by many oscillation scenarios. Neutrinoless double beta decay tests the charge conjugation properties of neutrinos, new CP violating phases, and a variety of beyond-the-standard-model phenomena.

The 0.01 eV goal requires sensitivity to half lives in excess of 10^{28} years. This in turn requires source masses ~1000 kg and unprecedented suppression of cosmic ray and radioactivity backgrounds. Several of the most promising experiments need enriched isotopes. Thus the scale and cost of future experiments are significant.

In Europe two promising experiments are Cuore, a bolometric detector using natural Te, and Genius, a germanium diode detector. Construction of prototypes for these experiments is underway. Both will be sited at Gran Sasso. Three experiments under consideration in the US are Majorana, EXO, and Moon. Majorana is an array of individually cooled enriched Ge counters with a total ^{76}Ge mass of 500 kg. Crystal segmentation and pulse-shape analysis is used to suppress backgrounds. EXO will employ 10 tons of Xe, enriched to 80% in ^{136}Xe,in a high-resolution TPC. Spectroscopic single ion tagging of the daughter Ba ion will provide additional background suppression. Moon, a joint Japanese/US effort, is a Mo foil/scintillator sandwich with a mass in ^{100}Mo in excess of 1 ton. An alternative design, a Mo-loaded scintillator, is also under discussion.

Depth and other requirements

These next-generation experiments vary in their depth requirements according to the specificity of the signals employed. Current Ge experiments indicate that Majorana will require depths in excess of 4000-4500 mwe. Estimates for EXO are 2000 mwe, though the proponents intend to verify background rates in a prototype experiment before selecting a final site. Estimates for Moon, which also detects solar neutrinos, are 4000 5000 mwe, with cosmic ray production of ^{91}Mo being troublesome.

Over the past 40 years experimental sensitivities have improved by about a factor of 10 every eight years. Thus, beyond the Majorana/EXO/Moon decade, progress will require further background improvements. If cosmic ray backgrounds are mitigated by depth alone, the need will be an additional 1600 mwe each decade.

Next-generation experiments require modest floor space (~250-500 m^2), careful attention to ventilation, low-level counting facilities, and, in certain cases, facilities for fabricating or storing materials deep underground.

EarthLab: A Subterranean Laboratory and Observatory for Life, Fluid Flow and Rock Processes

Coupled Processes in the Earth at Depth
Life at Depth
Fluid Flow and Transport at Depth
Rock Deformation at Depth
Mineral Resources and Environmental Geochemisty
Potential for Scientific and Engineering Innovation
Education and Outreach

The Earth is vigorous with active geologic processes that continuously and endlessly change the landscape and deep crust. We have limited direct observation of microbial organisms that live in the deep subsurface, of rock deformation, and of fluids that flow through these rocks. Furthermore, fluid flow, rock deformation, geochemical and biological processes are all coupled in complex ways. A laboratory and observatory in the deep subsurface (EarthLab) would provide an unprecedented opportunity to observe and study the evolution of geomechanical, hydrologic, geochemical and biological processes for the crust from the Earth's surface to the limit of habitable depths. Such a facility would be the only one in the world where long-term, in situ geomicrobiology, biogeochemistry, hydrological, and thermal/mechanical experiments could lead to the development of a fully coupled, thermal, hydrologic, mechanical, chemical and biological mass and energy transport model. The lab would also provide a here-to-fore previously unattainable resource for multi-disciplinary and multi-institutional investigations for the international earth and biological scientific communities. One of the primary goals of EarthLab is to provide an experimental and intellectual foundation for investigating the origin and bounds of life as well as to develop practical applications for the bioremediation, biotechnology and pharmaceutical industry. Other applications include new geophysical tools for characterizing the subsurface, new drilling technologies and engineering technologies for subsurface construction. Integral to the scientific goals of EarthLab will be a very active program to foster education and training for future generations of scientists and teachers from pre-college to post-graduate, focusing on those groups that have remained underrepresented throughout the 20th century. To accomplish its goals the activities of EarthLab must be closely linked and integrated with those of the physics community and with other regional academic centers in order to take full advantage of shared technological infrastructure, intellectual prowess and educational outreach capabilities. The principal requirement for EarthLab is a large-scale underground excavation where drilling and coring can take place, preferably an abandoned, deep mine or a custom excavated facility down to a depth of at least 2.5 kilometers, lateral extents on the order of kilometers, and access to heterogeneous, fractured crust throughout so that the hydrological, biological, geochemical and geomechanical interfaces can be studied as a function of depth and volume.

Coupled Processes in the Earth at Depth

Most earth processes are coupled. For instance, tectonic forces cause rocks to bend and fracture, in turn altering the permeability and porosity of the rock, and therefore the pressures, directions and rates of fluid movement. Changes in fluid pressures cause changes in the rock's elastic response to deforming forces, which control movement along faults and, finally, earthquake frequency and magnitude. Fluid flow is also important to the distribution of environmentally and economically important elements and compounds in the crust, many of which are dissolved in and precipitated from hot waters.

Life at Depth

The relatively recent discovery of deep subsurface microbial communities and what appears to be a subsurface biosphere has opened a new scientific frontier where earth sciences, chemistry, physics and biology merge to provide insights into how life on this planet, and even extraterrestrial life, may have originated and evolved over billions of years. The geological isolation of these deep subsurface microbial communities offers the potential to answer questions on the origin of life and its diversity as well as constraining the possibilities for life beneath the surface of Mars and other planetary bodies. In addition to the role of microorganisms in shaping the life forms on earth, the importance of microorganisms in the dissolution and formation of minerals is only now becoming recognized as geomicrobiology comes to the fore. Advances in our understanding of the origins, diversity, distribution and function of microorganisms in deep, often extreme, subsurface environments will rapidly expand our knowledge of geomicrobiological and biogeochemical processes on Earth and beyond.

This expansion can only occur if the coupling between these processes and those of the rock mass and fluids can be determined experimentally in situ. Certain minerals may provide nutrients for microorganisms, and fluids may deposit the microorganisms on those minerals and nutrients. Alternatively, the flow rates of fluids that are carrying nutrients to the organisms can be affected by changes in the local permeability and porosity field. The microorganisms in turn may precipitate minerals or generate gas that will alter the permeability and hence the fluid flow. Fluid flow may dictate the temperature at depth, therefore dictating whether thermophiles and hyperthermophiles can exist. Temperatures typically change slowly, but if the change is more rapid than the ability of the organisms to migrate, then the microorganisms must either adapt or expire. Fracture propagation may also impact subsurface microbial communities by altering the fluid flow, exposing fresh mineral surface to redox reactions and providing fresh mineral surfaces and aqueous and gaseous energy sources to the microorganisms. EarthLab would be the only facility in the world where these processes could be delineated at depth.

Fluid Flow and Transport at Depth

It is well known that fluid flow and transport are active at deep depths in the subsurface. However, the nature of that flow, its range of rates, and the role deep flow and transport play in other processes are largely unknown, because it is extremely difficult to measure. Direct observations and experiments in the subsurface are rare inasmuch as the earth's surface and drill holes are typically the only venues available for study. Unfortunately, samples of deep rocks obtained from drill holes are usually very small and have been disturbed greatly by the drilling process, making them poor materials for testing of factors that control fluid flow. EarthLab, however, would completely revolutionize the field by providing temporal and spatial measurements of previously unthinkable quality. Associated with deep flow and transport are several important societal concerns, including drinking water and irrigation water supply, hazardous and nuclear waste disposal, and remediation of contaminated groundwater. Additionally, the hydrologic science community needs a deep underground laboratory to study fundamental processes that after decades are still only understood in the simplest of terms, including recharge and infiltration, fracture permeability, physics of multi-phase flow, flow in fracture networks and characterization of the networks, verification of well test and tracer test models, characterization of active flow systems and paleo-flow systems, coupling of flow, stress, and heat, and storativity and transmissivity of tight rocks.

Borehole measurements, including those of geophysical properties, determine rock properties at a point but do not give information about the large volume of rock between the boreholes. Problematically, many of these properties and processes appear to vary depending on the size of the spatial scale at which they are evaluated. EarthLab would directly address this scale-dependence by providing tens of cubic kilometers of subsurface that could be interrogated. For instance, hydraulic, tracer, and geophysical imaging tests over the entire volume of the laboratory may be used to characterize rock structure, fracture connectivity, and transport properties, and their variability with scale, with depth, and with distance across the excavation-disturbed zone. The ability to investigate the rock package directly after imaging or performing tracer tests will result in improvements to the techniques that may be applied in other investigations as well as by the oil and geothermal industry.

Rock Deformation at Depth

Rock deformation deep in the subsurface is not well characterized, except through proxy methods such as seismic tomography. Except for a limited number of deep mines outfitted with extensometers, active rock strain can only estimated by surface based methods such as InSAR (satellite-generated Interferometric Synthetic Aperture Radar) and GPS (Global Positioning System data and associated analysis). EarthLab is needed to permit continuous, direct measurements of rock strain, and to provide an opportunity to evaluate factors that control that strain. As with permeability, how rock strain and stress vary as a function of position and sampled volume (measurement scale) are not well understood because sufficiently large volumes of rock at depth have not been adequately measured or characterized yet.

Access to the large rock volume in EarthLab will permit testing of the hypothesis that the Earth’s crust is "critically stressed", that is, some portion of the rock is always close to failure by fracture. Repeated shearing of such fractures can keep flow paths open that might otherwise close by mineral cementation. The most significant rock permeability at depth, therefore, occurs in areas of "critically stressed" fractures. Mapping fractures, stress, and fluid flow within the subsurface will permit confirmation and extension of theory associated with critical stress.

The primary benefit of siting EarthLab at the same site as proposed neutrino science facilities is that the excavation of large detector cavities provides the perfect experiment for observing 4-D rock deformation on an unprecedented scale. Hydraulic, tracer, and geophysical characterizations of transport parameters will be performed concurrent with cavern-enlargement. These data will be used to define the form of the coupling between mechanical and thermal effects, and hydraulic transport parameters, as well as provide opportunities to improve the interpretation and applications of the measurement techniques. Following excavation associated with laboratory construction, instrumentation arrays installed over the lateral and depth extents will be used to monitor the long-term passive response in the stable zone surrounding the detectors.

Mineral Resources and Environmental Geochemisty

Many of the mineral resources on which society depends are formed or concentrated by fluid flow in the subsurface. These concentrations reflect both chemical and physical processes. For instance, oil, natural gas and some brines are localized in the crust largely by their physical response to fluid flow. Most metals, such as iron, copper and gold, are localized by chemical processes involving dissolution and subsequent deposition of minerals containing these metals. In both cases, the fluid flow system that concentrates the mineral resource gathers material from a large volume of rock and concentrates it in much smaller volumes that we call mineral deposits. Although considerable progress has been made in understanding the processes that form mineral deposits by observation of fossil systems, we badly need to study these processes in an active environment. In most cases, these active environments, such as geothermal areas, are too hot and deep for direct study. EarthLab would allow direct testing of processes that have been inferred from theory.

Fluid flow through rocks is also critically important to the release and concentration of metals and organic compounds that are of environmental concern. Most such releases take place because rock from deep in the crust is exposed to water and oxygen, causing minerals formed at depth to decompose. The most widely know of these processes, acid mine drainage, results when pyrite (FeS_2) is oxidized by near-surface waters. Most studies of acid mine drainage and related processes have been confined to the points at which these waters exit mines or other underground sources. EarthLab would allow more direct observations of the early stages of these processes at depth, which will lead to better methods to control or stop dispersal of elements and compounds by these processes.

The current thermodynamic and kinetic data base that is used to model active or ancient hydrothermal or fluid/mineral processes is woefully inadequate to accurately model "real" systems. EarthLab will provide a unique experimental venue whereby laboratory measurements of these parameters can be directly validated in situ. For the first time geochemists will be able to directly calibrate the accuracy of their experimental extrapolations.

Potential for Scientific and Engineering Innovation

EarthLab will generate new technological innovations as a result of deep subsurface scientific and engineering studies. Some possible innovations and advances include

- New genetic materials, novel microorganisms and biotechnology applications
- Analytical techniques for geomicrobiology and exobiology
- Natural resource recovery
- Drilling and excavation technology
- Novel uses of underground space
- Mine safety
- Subsurface imaging
- Environmental remediation

Even construction of EarthLab stands to provide new innovations and advances. The regions surrounding the proposed laboratory reaches will be instrumented prior to enlargement. Instrumentation will be installed in coreholes adjacent to excavated blocks, and continuously monitored thereafter for excavation-induced displacements, microseismic activity, temperatures, and fluid pressures, and to recover aqueous and particulate samples. New sensor technology can be designed specifically for these purposes. Efficacy of different prototypes may be tested and compared.

Education and Outreach

An underground science laboratory is an opportunity to affect a large segment of the public ranging from students at every level to the general community. Educational and Outreach (E&O) activities will engage, recruit, and retain the next generation of science and engineering professionals. It will enlighten and provide educational materials for our educators, community officials and legislators and will educate and involve the public in the world of physics, biogeochemical processes, and geologic environment of the deep underground environment. The fact that E&O is an integral part of the proposed underground laboratory will provide cooperative and collaborative synergisms not afforded most research programs. Thus, more long-term hands-on immersion into the scientific research will be available for programs targeted to K-12 students and teachers, undergraduates, post-graduates, college teachers, and the general public. The underground site will appeal to a broader segment of the public than if it were aimed at people interested only in physics, geology or biology. For example, one might be able to examine the relationships between complex geology and life at various depths or observe the deepest physics experiments in action. EarthLab should provide public and scientific access to the underground, including the necessary infrastructure to move both large and small groups of people depending on the educational or outreach program (e.g. school field trips or undergraduate summer research opportunities). Access to the underground will provide the visitor with direct contact (physically) to the science and the scientists where the action is located and thus will produce lasting impressions and impacts upon the visitor. The many E&O opportunities will develop an appreciation for the multidisciplinary sciences involved in the subterranean environment. This appreciation should include the development of a general understanding of the goals of the scientific research projects and a feeling that these projects are worthwhile. Positive impacts on students, educators, and the public will be seen through improved scientific literacy and an enhanced understanding of active processes in the subsurface. The national economy, educational system, and scientific communities will benefit from the increased numbers of science and engineering professionals, especially members from under-targeted, underrepresented groups.

Summary

Direct access for the study of deep subsurface processes is limited to the few deep mines in the world and the small number of deep boreholes that penetrate the crystalline basement. Work in deep mines is difficult because mines are primarily industrial operations and because accessing areas of most interest often constitute serious engineering challenges. Work with deep core samples is complicated by the small sample sizes, disturbance by drilling, and because it is often difficult to extend the interpretations beyond the immediate vicinity of the borehole. Because the deepest boreholes are typically drilled during petroleum exploration efforts, the observation "window" borehole is only open for a very short period, precluding repeated visits. Examining larger-scale subsurface processes is currently accomplished using methods such as measurements of seismic velocities and attenuation, satellite-based remote sensing, gravity, magnetic, and electrical methods. These techniques are used to infer Earth structure and processes, but all of them may be considered remote sensing activities. EarthLab will provide an opportunity to go beyond point sampling and to verify remote sensing methods with direct observation and measurement.

In total, a large-volume, long term underground laboratory is needed to advance earth science and engineering studies beyond the status quo. Much like surgery permits a physician to examine internal bones and organs recognized on X-rays or CAT scans, EarthLab will be a fully instrumented, dedicated laboratory and observatory for scientists to examine Earth's active interior.

Dark Matter Working Group Executive Summary (NeSS ’02)

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Introduction

No currently observed particle is a suitable candidate for cold dark matter. The solution to the non baryonic dark matter problem, both in the universe as a whole, and in our own galaxy, may be resolved by physics found at the intersection of astronomy, high energy particle physics, and cosmology. The main candidates for this dark matter are relic particles generated, in great abundance, shortly after the Big Bang. Currently, there are 20 operating experiments designed to perform the direct detection of these particles being conducted at all the underground physics laboratories worldwide (bar one). One of them is sited at a US underground laboratory, although US sourced funding is made to six experiments. Existing results have put significant constraints on the allowed particle theories of dark matter, with one experiment claiming a positive observation, yet to be confirmed by other experiments.

The planned dark matter experiments that were discussed at this workshop would be able to cover most of the parameter space of major theoretical proposals. The new physics required for particle dark matter is also expected to be discovered in the next round of high energy accelerator experiments (LHC, NLC). Theoretically and experimentally there is great complementarity between direct detection and accelerator programs. Although future accelerator experiments may map out the permissible theoretical possibilities for dark matter, only direct detection experiments can positively identify the dark matter particle, and elucidate the earliest stages of the cosmological evolution of the universe.

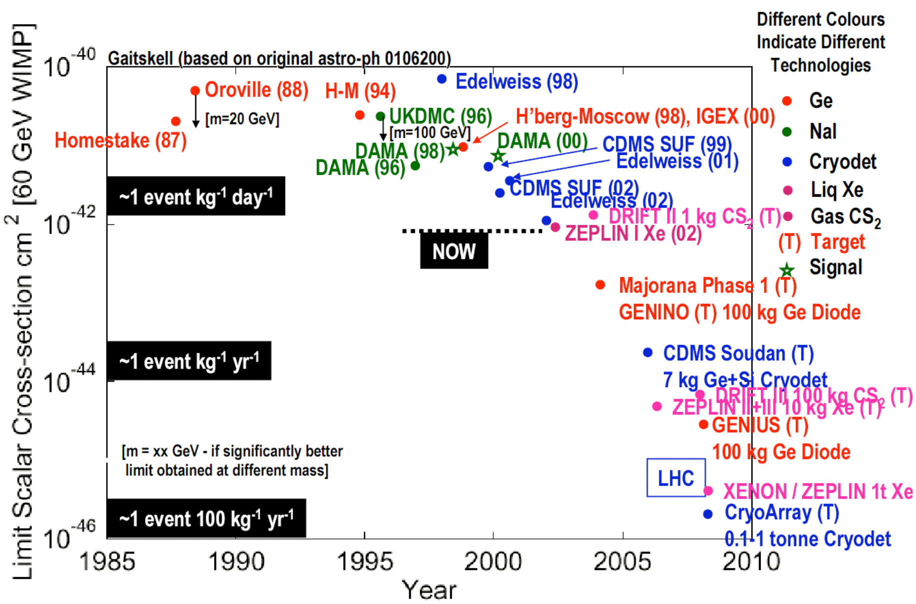

Figure 1. Experimental sensitivities (90% upper CL) for 60 GeV WIMP-nucleon scalar cross-section (10^{-46} cm^2 is equivalent to 10^{-10} pb) versus times of publications. (Not meant to be an exhaustive selection.) The labels in the boxes give the equivalent event rates in Ge assuming a low recoil energy threshold >10 keV. Also shown are a selection of the maximum sensitivities for a number of planned experiments. The standard vanilla assumptions are made about the WIMP population in the Galaxy (Lewin&Smith): local density of 0.3 GeVcm^{-3}, and a characteristic velocity of 230 kms^{-1}. The SUSY physics reach of the 1 tonne experiments will be broadly comparable to that of the LHC which is due to report results before the end of this decade.

Astrophysics Motivation and Particle Dark Matter Theory

Astrophysical measurements have progressed to the point that they now provide a reliable inventory of the contents of the universe. The non-baryonic component of dark matter in the universe is estimated as Ω_{nbdm} = 0.29+/-0.04 and this result is supported by a number of independent astrophysics measurements. It is strongly favoured that this same dark matter is the dominant matter component in our own galaxy.

For direct dark matter detection experiments, which search for the nuclear recoils produced in elastic scattering of weakly interacting massive particles (WIMPs) from nuclei, it is crucial to estimate the WIMP-nucleon cross section. This cross section, along with the density and velocity distribution of WIMPs in the vicinity of the solar system, determines the expected detection rates in a given detector (see Fig. 1).

A number of particle dark matter candidates were discussed at the workshop. In one of the favoured models, the minimal supergravity (mSUGRA) framework, which arises as a low energy limit of supergravity theory, the candidate WIMP is the lightest neutralino. In general it was found that the spin independent neutralino cross sections (for candidates that satisfy all accelerator and cosmological constraints lie between 10^{-7} and 10^{-10} pb (see e.g. hep-ph/0202110, 0204187). A small part of the mSUGRA parameter space can lead to some model cross sections below this value, however, the recent muon magnetic moment result from BNL strongly favours cross sections above 10^{-10} pb.

WIMP cross sections in the 10^{-7} and 10^{-10} pb range also arise in a wide class of models with different types of supersymmetry breaking (hep-ph/9708264, 9906527), Q-balls (hep-ph/0205044, 0203179), extra dimensions (hep-ph/0206071, 0207125). Thus, detectors sensitive down to 10^{-10} pb (equivalent to 10's of dark matter recoil events/1 tonne/year, see Fig. 1) will be able to examine most of the theoretically expected models.

Direct Detection Experiments and Underground Laboratory Requirements

Some 20 operational dark matter experiments are currently being conducted, with at least one experiment in each of the underground physics laboratories worldwide (bar one). The current detection limit (90% CL sensitivity) is ~0.3 events/kg/day which corresponds to a normalized scalar cross section of ~10^{-6} pb. This sensitivity has been achieved by the Edelweiss experiment by observing no nuclear recoil candidate events above 20 keV recoil energy for 7.3 kg-days of exposure of a single 0.33 kg Ge cryogenic detector. A similar sensitivity is also achieved by the ZEPLIN I experiment with 230 kg-days of exposure, using single phase liquid Xe of 3.1 kg fiducial mass. New phases of existing experiments allow for final target masses of typically 10–50 kg with a reach ~30x better (~few 10^{-8} pb) than current limits, that should be achieve within the next 5 years.

Technology / Collab. Name	CURRENT Fiducial Mass Goal (Now)	2001→ Funding source	Underground Location	PROJECTED Mass Goal	2005→ Underground Location
Liquid Xe					
XENON	100 kg (-)	US	**	1000 kg	**
ZEPLIN	30 kg (3 kg)	UK/US/EU	Boulby,UK	1000 kg	Boulby,UK
XMASS	20 kg (1 kg)	Japan	Kamioka,Japan	1000 kg	**
Cryogenic (T<1K)					
CDMS/CryoArray	7 kg (1 kg)	US	Soudan,US	1000 kg	**
EDELWEISS	7 kg (0.7 kg)	France	Frejus,France	35 kg	Frejus,France
EuroCryo Collab		Europe	**	1000 kg	**
Gas TPC					
DRIFT	3 kg (0.2 kg)	US/UK	Boulby,UK	100 kg	**
HP Ge					
MAJORANA	40 kg (2 kg)	US	**	500 kg	**
GENIUS	40 kg (5 kg)	Europe	Gran Sasso,Ity	1000 kg	Gran Sasso,Ity

Table 2 The table includes a subset of the currently operating dark matter experiments (total of 20), that were discussed in detail at the workshop. The projected scale up plans (2005 onwards) of those experiments are also shown. A "**" in the location column indicates that no strongly preferred site has been selected. A complete list of experiments is available in an appendix to this document.

In addition, a number of planned experiments exist for 100 kg-1 tonne experiments, some of which would be able to reach down to the 10^{-9}–10^{-10} pb early in the LHC era, at a sensitivity which would include most currently favoured theoretical models discussed above. The field is dominated by experiments that will use the ability to discriminate electron recoil events (background) from nuclear recoil events, although two experiments based on HP Ge ionization detectors will be able to reach down to 10^{-9} pb before pp solar neutrinos become an irreducible background. Some of the existing and proposed experiments are listed in Table 2. If WIMPs are discovered, an experimental period of at least 5–10 years event data collection from a range of these experiments may permit the determination of the mass, and characteristic velocity of the particles, as well as allowing comparison with SUSY accelerator data. Annual/diurnal energy and direction modulations of the recoil signal will be performed, along with studies of the cross section dependence on different target elements/isotopes.

Future dark matter direct detection experiments must be operated at deep underground laboratories in order to reduce the gamma and, neutron fluxes generated by cosmic–ray muons. For most planned experiments (down to 10^{-10} pb sensitivity) conventional thick Pb/Cu shields, and hydrogenous neutron moderator material can be used to reduce to acceptable levels the external gamma radiation (from U/Th/K in the rock/cavern materials), and the μ-induced neutrons (E_n<10 MeV), respectively. This assumes that the detectors are able to reject residual gamma events at 99.99% using a combination of electron vs nuclear recoil discrimination, and possibly an active veto region directly surrounding the fiducial volume. In order to achieve comparable performance, experiments unable to discriminate between nuclear and electron recoils will require more innovative shields, and construction methods.

Controlling the internal radioactivity of detector arrays will be a challenge. The target materials, and some structural materials, will have to be selected for their low levels of U/Th/K. (For electron recoil discriminating detectors the target will be ~10^{-12} g/g U/Th, and 10^{-14} g/g for non-discriminating detectors.) Cosmogenic activation of the materials will also have to be controlled. This will require the final refinement, or fabrication of certain materials in shallow underground laboratories. Examples include the growth of Ge crystals underground, and a program for the purification (including removal of Kr) from Xe. Minimization of surface contamination of detectors, and local components, by beta emitters, will also require advanced handling and screening procedures. Projected requirement as ~<1 beta event/m^2/day on surfaces exceed currently available screening levels.

The minimum depth of successful operation will be related to the residual flux of high energy (50–500 MeV) neutrons from muons interacting in the surrounding rock. The neutron flux is directly proportional to the muon flux for depths >2 kmwe. A more complete assessment of the depth issue is contained in an appendix to this report, however, in conclusion, for the next generation of dark matter experiments, with a WIMP-nucleon cross section goal of about 10^{-10} pb, a 4500 mwe site would most likely provide sufficient shielding against the hard, cosmic-ray induced neutron spectrum. Shallower sites (1700-4500 mwe) may be sufficient with more complicated experimental shield designs. There remains the concern that a possible systematic leakage of muon related neutron events could render a shield less effective than required, although current investigations have yet to identify such a mechanism. A deeper site (e.g. 6000 mwe) would perhaps provide a safety net against residual muon related backgrounds, and may be necessary for next–next generation experiments that plan to reach beyond 10^{-10} pb, and also those which perform precision experiments on the dark matter particles.

The typical footprint of a 1 tonne dark matter experiment will be relatively modest, since the total active volume is <1 m^3 for solid/liquid targets. Shielding materials with a thickness of up to 2 m, and the deployment of sub-modules of say, 100 kg fiducial each would require a total experimental floor area of 10x30 m^2, plus under/over ground staging areas and office space. A comparable mass gas based detector will have a much larger footprint, which will be determined by the gas pressure (typically <<1 atm.). The individual cost of the current generation of dark matter experiments in construction/operation (worldwide), on a US-style cost basis, breaks down in the range: construction capital 5-15M$, operating 2-4M$/yr and personnel FTE 15-40. Current projections for the likely cost of 1 tonne experiments are: construction capital 20-50+M$, operating 4-8M$/yr, personnel FTE 30-60. It should be emphasized that the experiments have benefited from seed R&D funding extending over more than the last 10 years, and will continue to need this type of funding outside the main project costs.

The implementation of a range of experiments for dark matter detection is necessary, both to maximize the information gathered on the properties of the particle dark matter, and also to spread the risks associated with specific detector schemes being hampered by systematic limitations. The best experiments for particle dark matter searches require detector technologies that are pushed to the very limit of our current capabilities.

The planned 50 kg–1 tonne dark matter experiments can be considered "intermediate" in scale and will particularly benefit from the support by a national lab infrastructure, since the burden of providing all ancillary services internally may not be realistic. The availability of technical staff, and engineers to provide on-site operations support will be crucial in ensuring the efficient operation of the experiments, without placing undue burden on other participating institutions. The lack of local personnel has lead to delays in many of the existing experiments. The availability of "one–stop-shop" background screening services, or the provision of specialized labs which will permit the installation of collaboration developed screening systems, will allow faster progress. There is also expected to be considerable overlap in the screening requirements of parallel dark matter, double beta decay and low energy solar neutrino experiments.

Education & Outreach

The essential elements of the dark matter problem and its relation to astronomy and early universe cosmology can be readily understood. As a consequence, it seems to particularly catch the public imagination, and forms an excellent basis for education and outreach. The apparent contradiction of performing astrophysics deep underground only adds to the interest.

A number of ideas were discussed at the workshop relating specifically to dark matter, and also to the wider context of particle astrophysics, cosmology and particle physics. The group felt that an underground laboratory would provide a strong central resource to better leverage, and coordinate, the E&O efforts of the independent groups. The lab could provide resources for short video production (to be streamed over internet), mobile demonstrations for schools, and science museums, and also a central web index/repository. The theme of the related E&O programs would include the ideas that the discovery of particle dark matter would explain an important aspect of what happens during the big bang, influencing the universe's subsequent evolution, and would correlate with the experiments at the LHC (and other accelerators).

Conclusion

The dark matter detectors currently being executed (2002-)/planned(2005-) can investigate most of the parameter space of current particle models for dark matter. If any of these models have validity, the direct detection of dark matter will open a window on the early universe, inaccessible by other means of observation, probing physics at a time well before big band nucleosynthesis. The logistical and technical support that will be provided by a national underground laboratory is essential for the successful detection of particle dark matter in the US. The discovery of particle dark matter will lead to a period (extending beyond 2020) of WIMP "astronomy". The particle properties, and their local velocity/density distributions, will be measured using a range of detector techniques currently operating/under development (exploiting the recoil energy measurements, and related annual/diurnal/directional modulations), which will stretch well into the lifetime of the underground laboratory.

Appendix 1 (Dark Matter Working Group): Laboratory Depth Requirements

The most important cosmic-ray muon background for direct dark matter detection experiments is the fast neutrons (20-500~MeV) produced outside the detector shielding. These high-energy "punch-through" neutrons are difficult to tag with a conventional local muon veto system, since they can be produced many meters into the cavern rock, and still emerge into the cavern space. To counteract these neutrons, thick active shields and wide umbrella veto systems deployed in the tunnel rock are under study. The high energy neutrons produce lower-energy neutrons of a few MeV, by scattering in the materials surrounding the detectors. These low-energy neutrons can produce the same signals in the central detectors as WIMPs.

It should be noted that, many current or proposed dark matter experiments can discriminate effectively against other backgrounds that deposit energy through electromagnetic interactions, reducing, by many orders of magnitude, the `raw' low background levels inside the detector system. Consequently, the background from the fast neutrons may be the limiting background for these experiments.

For example, the sensitivity of the CDMS experiment at the shallow Stanford Underground Facility (16 mwe) is limited by these external neutrons {cdmsprd}, in spite of a more than 99.9% efficient muon veto system. EDELWEISS is an experiment similar to CDMS, but it is already located at a deep site at the Laboratoire Souterrain de Modane in the Frejus Tunnel (4800 mwe). Because of the experiment's much greater depth, EDELWEISS has detected no WIMP-candidate events after an exposure of 7.4 /kg/d {edel2002}. The latter experiment is currently the most sensitive direct dark matter search.

Estimating the size of the "punch-through" neutron background for the next generation of deep experiments is uncertain in a range of around a factor 3, at present. The muon flux is well measured, but the neutron yield and energy spectrum are not.

The muon flux at the Earth's surface is about 170 muons/(m^2 s), with an average energy $\langle E_\mu \rangle \approx 4$ GeV. At the Homestake site at 4500 mwe, this flux is reduced to about 800 muons/(m^2 yr), the muon spectrum being much harder with a mean energy $\langle E_\mu \rangle \approx 350$ GeV. For comparison, at WIPP (1700 mwe) the muon flux is 100x higher, and at Homestake deep level (6200 mwe) the muon flux is 20x lower.

Fast neutrons are produced in the rocks surrounding the experiments by one of the following processes: muon interactions with nuclei leading to nuclear disintegration, neutron emission by a nucleus following a muon capture, muon elastic scattering with bound neutrons, photo-nuclear interactions associated with electromagnetic showers generated by muons, and secondary neutron productions in these processes. The neutron yield as a function of the mean muon energy can be approximated by a power law $N \sim \langle E_\mu \rangle^{0.75}$ {aglietta89}. While there are many theoretical estimates of the energy spectrum of high-energy neutrons at deep sites, only few measurements exist. An empirical function which reproduces existing measurements fairly well has been found in {gratta_fluka}, using the standalone FLUKA {fluka} Monte Carlo program. Comparison of these estimates to measurements suggests that there is perhaps as much as a factor of 3 uncertainty on the expected fast neutron background, particularly at large depths.

Based on such estimates and Monte Carlo simulations, the CDMS~II experiment at the Soudan mine (2080 mwe) should detect at most 8 single-scatter events due to external, high-energy neutrons, after an exposure of 6.8 kg yr with 42 detectors {gaitskell01}.This number is more than small enough to allow the experiment's sensitivity goal of $3\mathrm{x}10^{-8}$ pb, which is 30x better than current sensitivity limits $\sim 10^{-6}$ pb. A 1 tonne Ge experiment would expect at most 1170 single-scatter events/(tonne yr) at the same depth. The neutrons will usually multiple-scatter in experiments with good granularity; detailed Monte Carlo simulations of such experiments are needed to determine the rejection due to multiple scattering.

As a comparison, for a WIMP cross section of 10^{-10} pb, about 10 WIMP events/(tonne yr) are expected. (This is a level of sensitivity 3000x better than existing experiments, and would allow the probing of the majority of currently favored SUSY models, that would also be accessible by LHC.) Thus, even with a rejection efficiency of one order of magnitude due to multiple neutron scattering, the rate due to high-energy neutrons would still dominate over the expected WIMP rate at a 2000 mwe depth.

The simplest way to reduce the neutron background to an acceptable level is increased depth. At the 4500 mwe level of the NUSL site, the neutron flux is expected to be at least a factor of 25 lower than at Soudan. It would result in about 50 interactions due to high-energy neutrons per tonne and year. If an additional factor of ten reduction due to vetoing of multiple scatters can be assumed, the high-energy neutron induced background rate would be a factor of two lower than the expected WIMP rate at the 10^{-10} pb cross section. The deep NUSL site (6500 mwe) would offer an additional factor of about 20 reduction in the hard neutron flux.

Alternatively, at a site more shallow than 4500 mwe, elaborate shielding and vetoing would be able to reduce the hard neutron background by the extra 1-2 orders of magnitude required. A thick (1-2 m) scintillator active veto around the detectors could tag high energy neutrons as they penetrate inwards. As a second approach, the cavern rock itself, or an outer heavy passive shield, could be instrumented with additional veto detectors in order to catch some part of the shower associated with the muon that generated the neutron. Finally, as mentioned above, increasing the granularity of the dark matter detectors would allow better rejection of neutrons through increased multiple-scatters. The efficacy and cost of these methods is in the preliminary stages of being studied, however, it is reasonable to assume that the cost of these additional external vetos, which employ more standard detector technology, will be less than the construction cost of the very much more sensitive/lower radioactivity dark matter detectors at the center of the assembly.

In conclusion, for the next generation of dark matter experiments, with a WIMP-nucleon cross section goal of about 10^{-10} pb, the 4500 mwe NUSL site would most likely provide sufficient shielding against the hard, cosmic-ray induced neutron spectrum. Shallower sites (1700-4500 mwe) may be sufficient with more complicated experimental shield designs. There remains the concern that a possible systematic leakage of muon related neutron events could render a shield less effective than required, although current investigations have yet to identify such a mechanism. A deeper site (e.g. 6000 mwe) would perhaps provide a safety net against residual muon related backgrounds, and may be necessary for next–next generation experiments that plan to reach beyond 10^{-10} pb, and also those which perform precision experiments on the dark matter particles.

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Appendix 2 (Dark Matter Working Group):
Complete List of Operating/Planned Dark Matter Search Experiments

{Table is preliminary – please consult working group leaders for final revisions}

Site	Experiment	Technique	Target	Status
Baksan (Russia)	IGEX	Ionisation	3kg Ge	Operational
Bern (Switzerland)	ORPHEUS	SSD	0.5kg Sn	Operational
Boulby (UK)	NaI NaIAD ZEPLIN I ZEPLIN II/III ZEPLIN-MAX DRIFT-I DRIFT-II	Scintillator Scintillator Scintillator Scintillator/Ionisation Scintillator/Ionisation TPC TPC	5kg NaI 50kg NaI 3kg Lxe 30kg/7kg Xe 1000kg Xe 0.2kg CS_2 3kg CS_2	Completed Operational Operational Construction Planned Operational Planned
Canfranc (Spain)	COSME IGEX ANAIS ROSEBUD	Ionisation Ionisation Scintillator Thermal	0.2kg Ge 2.1kg Ge 107kg NaI Al_2O_3,Ge,$CaWO_4$	Completed Operational Constrcution Operational
Frejus (France)	Saclay-NaI EDELWEISS I EDELWEISS II	Scintillation Thermal/Ionisation Thermal/Ionisation	10kg NaI 0.07kg Ge 1.3 kg Ge	Completed Completed Operational
Gran Sasso (Italy)	Hdlberg/Mscw HDMS Genius DAMA LIBRA Xenon CRESST-I CRESST-II CUORICINO CUORE	Ionisation Ionisation Ionisation Scintillation Scintillation Scintillation Thermal Thermal/Scintillation Thermal Thermal	2.7kg Ge 0.2kg Ge 100kg Ge 100kg NaI 250kg NaI 6kg Xe 1kg Al_2O_3 10kg $CaWO_4$ 40kg TeO_2 760kg TeO_2	Completed Operational Planned Operational Construction Operational Oprational Construction Construction Planned
Otto-Cosmo (Japan)	Elegants V Elegants VI	Scintillation Scintillation	NaI 750kg CaF_2	Operational Operational
Rustrel (France)	SIMPLE	SDD	1g Freon	Operational
Stanford (USA)	CDMS-1	Thermal/Ionisation	0.1kg Si, 1kg Ge	Completed
Soudan (USA)	CDMS-II CryoArray	Thermal/Ionisation Thermal/Ionisation	1kg Si, 7 kg Ge 1000 kg	Construction Planned
SNO (Canada)	PICASSO	SDD	1g Freon	Operational

Our thanks, to Angel Morales, Nigel Smith, and Rick Gaitskell for providing this information.

Executive Summary: Neutrino Oscillations and Mass, and CP Violations
Working group leaders: Vernon Barger and Mike Shaevitz

Abstract: Our working group reviewed the status and prospects for measurements of neutrino masses and mixings, mainly concentrating on terrestial neutrino beam sources, and considered how this science couples to an underground laboratory.

Why are neutrino oscillation measurements important? Neutrino masses and mixings give a window on physics at high mass scales: unification, flavor, and extra dimensions. Oscillation studies are essential to answer fundamental questions: Why are neutrino masses so small? Why are their mixings so large? Are there additional "sterile" neutrinos? Is there a connection between the lepton and quark sectors? Is there CP violation, T violation, or CPT violations in the lepton sector? Can the baryon asymmetry of the Universe, which is hard to generate from CP violation in the quark sector where the mixings are small, be a consequence of CP or CPT violation in the lepton sector?

Grand Unified Theories explain the smallness of neutrino masses by the see-saw mechanism in which a large Majorana mass ($m_M \approx 10^{14}$ GeV) and an electoweak scale Dirac mass result in a neutrino mass of m_D^2/m_M. Unification models may also contain extra sterile neutrinos that could be light. Other possiblities for neutrino mass generation include extra dimensions, in which right-handed neutrinos live outside of 3+1 space, and radiative neutrino mass generation with new particles and interactions. These ideas make very different testable predictions for the structure of the neutrino mass matrix.

Neutrino oscillations of three neutrinos depend on two mass-squared differences, three mixing angles, and a CP-violating phase. Atmospheric neutrino data determine $\delta m^2_{31} \approx 3\times10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \approx 45°$. Solar neutrino data determine $\delta m^2_{21} \approx 6\times10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \approx 30°$. Future measurements of $\nu_\mu \to \nu_e$ and $\bar\nu_\mu \to \bar\nu_e$ oscillations are crucial to determine θ_{13} (known to be $< 10°$ from reactor experiments), the sign of δm^2_{31}, and the CP phase δ. θ_{13} is now the key parameter for oscillation phenomenology; it determines whether there are matter effects and whether CP violation is accessible. Neutrino masses and mixings are also important in astrophysics in understanding supernovae, galactic structure formation, etc. Since neutrino oscillations only depend on mass-squared differences, measurements of tritum beta decay (the KATRIN experiment) or double beta decay are also needed to fix the absolute neutrino mass scale and thereby establish whether neutrino masses are hierarchical or degenerate.

A world-wide experimental program is underway to measure the neutrino oscillation parameters. The current oscillation experiments are K2K, that measures ν_μ disappearance over a 250 km baseline from KEK to the SuperKamiokande detector, and MiniBoone, that will search for the $\nu_\mu \to \nu_e$ appearance signal in the mass-squared region 0.2 to 1 eV^2 for which a signal was found by the LSND experiment. Upcoming long-baseline (730 km) experiments are NuMI/Minos at Fermilab and CNGS at CERN that will study ν_μ oscillations in the atmospheric δm^2 region. Near-term experiments will use off-axis beams, JHF to SuperK (22.5 kton) and NuMI/Minos (20 kton detector proposed). The next stage will be neutrino superbeam experiments, that may be combined with large proton decay detectors. Four such projects under consideration are: (i) BNL, with an AGS upgrade, to NUSL, (ii) Fermilab, with a proton driver upgrade, to NUSL, (iii) JHF (phase II) to a HyperK detector at the Kamiokande laboratory, and (iv) CERN Superconducting Proton Linac to Frejus. Future neutrino factories, using a muon storage ring, will provide the ultimate in sensitivity and precision in oscillation measurements.

We outline a roadmap for neutrino oscillation experiments. In Stage 0, the current near term program, NuMI and K2K check atmospheric oscillations and measure δm^2_{31} to a precision of 10% Also, MiniBoone makes a definitive check of the LSND effect and measures the associated δm^2 if the effect is confirmed. In Stage 1, the θ_{13} angle is measured or more tightly constrained. The NuMI/MINOS on-axis experiment probes $\sin^2 2\theta_{13} > 0.06$ at 90% CL. The NuMI and JHF off-axis beams can go down to $\sin^2 2\theta_{13} > 0.01$ at 90% CL. A long-baseline experiment from FNAL or BNL to NUSL with a 100 kton detector could have still better sensitivity. In Stage 2, CP violation and the sign of δm^2_{31} would be measured using superbeams and very large detectors (500 to 1000 ktons). This is feasible if $\sin^2 2\theta_{13} > 0.01$. Measurements of $P(\nu_\mu \to \nu_e)$ and then $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ are needed. The increased rates needed, especially for the $\bar{\nu}_\mu$ beam, make high intensity proton sources necessary. Finally, at Stage 3, measurements with a Neutrino Factory would probe $\nu_\mu \to \nu_e$ transitions and map out CP violation with precision down to $\sin^2 2\theta_{13} > 0.0001$.

For Stage 2, one would like to have baselines greater than 1200 km in order to more fully exploit information associated with matter effects. There are some tradeoffs between neutrino interaction rate and physics reach but there is good sensitivity to the oscillation phenomenology over a broad range of baselines. For NUSL, experiments using beams from Fermilab or Brookhaven can be used with complementary capabilities. Using higher energy beams with baselines greater than 1200 km can allow one to probe effects for more than just the first oscillation maximum and provide information simultaneously on CP violation and the sign of δm^2_{31}. It is also fairly clear that to unravel the ambiguities and correlations associated with matter effects and CP violation, the program will need measurements for two significantly different baselines. Since the detector cost will likely dominate the project, multiple baselines could be realized in the U.S. using beams from both Fermilab and Brookhaven.

There are some general requirements of neutrino oscillation experiments. First, a high intensity beam is needed with the energy initially tuned at the appearance oscillation maximum for the baseline. The neutrino sources would orginate from the present laboratories (BNL or Fermilab). There are many dectector sites possible, with longer baselines advantageous in resolving degeneracies of oscillation parameters that describe the same event rates. Second, many detector technologies do not need to be located underground. Due to the beam duty cycle, only small overburdens are needed to reduce the cosmic ray background. Third, Superbeam experiments to measure CP violation require very large and consequently costly detectors. It is natural to couple such detectors to proton-decay and supernova detectors. Then the detector needs to be in an underground laboratory. For the detector to be compatible with proton decay requirements some compromises may be necessary. Two types of detectors under consideration are water Cerenkov and liquid argon.

If MiniBoone confirms LSND, there will be three distinct δm^2 values which is beyond the the standard three neutrino scenario. More long and short baseline experiments will be needed to understand the phenomena. A possible solution is oscillations to sterile neutrinos, which can also be tested with better measurements of sterile components in the solar and atmospheric oscillations. Another extreme possibility is CPT violation, with LSND measuring anti-neutrino oscillations and solar experiments measuring neutrino oscillations. This scenario can be tested by measurements with both antineutrino (the KamLAND reactor experiment) and neutrino sources.

In summary, the neutrino program through 2010 will pursue the measurements of presently unknown oscillation parameters using long-baseline experiments. We need to measure θ_{13} and the sign of δm^2_{31} and to probe for CP violation. Some information will come from the present on-axis experiments from Fermilab to Soudan and from CERN to Gran Sasso. For example, NuMI/Minos reaches a sensitivity of $\sin^2 2\theta_{13} > 0.06$ at 90% CL. Then off-axis experiments will probe $\sin^2 2\theta_{13} > 0.01$ at 90% CL. The JHF and NuMI off-axis beams have narrow energy distributions that are tunable. We may also find the first evidence of CP violation in these experiments. The combination of data from these two baselines may be important in removing ambiguities in the oscillation parameter determinations. When all the neutrino mixing and mass parameters become known, we anticipate that a theoretical synthesis will be achieved.

Counting Requirements for Next Generation Solar Neutrino Experiments

A. S. Hamer

Future solar neutrino experiments will strive to lower thresholds well below the MeV level in order to detect the pp neutrinos. The experiments will all require real time counting capabibilities and have both charged-current (CC) and some neutral-current (NC) sensitivity. The neutral-current experiments by necessity must detect the neutrinos via elastic-scattering (ES) interactions. Stringent radiopurity requirements for the materials used in the construction of these experiments are needed. The choice of materials and the subsequent quality insurance during construction and assembly will in turn require the use of sensitive radio-assay techniques. The following discusses the ranges of counting technologies that will be required, along with sensitivities, for the next generation experiments.

Two strong candidates for CC detection are MOON and LENS. Both use passive detection methods. LENS for example will use Indium or Ytterbium targets, but loaded into liquid scintillator. To reduce backgrounds, the scintillator will have to be highly segmented. Purity requirements for the scintillator would be on the order of that used for Borexino or KamLAND (10^{-16} g/g U and Th). Similarly, the loading element will have to be of extreme purity as well. MOON will use Molebdium as a target. One possibility is to use Mo in the form of foils surrounded by large sheets of plastic scintillator. Purity levels for the inner detector volumes would have to be at the 10^{-13} g/g U and Th levels. These experiments will have to use techniques (NAA, etc.) similar to those used in Borexino. Also, because of the segmentation, surface contamination will be of concern and methods to assay and test these large surfaces will be required. Finally, both LENS and MOON will have to be sealed from Radon. All components in which there is a potential Rn migration path to the inner target and detection volumes will therefore have to be tested.

Candidates for ES detection are HERON, CLEAN, and TPC. Both HERON and CLEAN propose to use cryogenic fluids as targets. The advantage of such targets would be the ability to reach very high purity levels in the main target volumes and the defence of cryogens against the migration of radon. Both HERON and CLEAN would consist of a single large target volume which in turn would have a separate detection readout array. The concern in both experiments is therefore gamma-rays from the external support, cryostat, and readout hardware. For example, CLEAN would have a central target volume surrounded by a cryogenic containment and photoarray structure. This structure presumably would be as complex as that of the SNO detector and would require the assay of 100's of components. The counting sensitivity would be on the order of ??? for U/Th and ??? for K. Components would include those that make up the cryostat, the PMTs, the PMT bases, cables, etc. The material for the outer shield containment vessel would also have to be assayed. HERON would also require counting of cryostat parts as well as the thousands of optical/phonon readout detectors. In some instances large cryostat components would require whole body counting capabilities. The solar neutrino TPC project will also require very stringent purity with the overall levels not exceeding the 10^{-13} g/g U/Th. Parts would include the plastics, wires, etc. needed in the construction of a large TPC. Direct counting methods, enhave via neutron activitation analysis methods, would certaintly be required along with the ability to test for radon emanation.

Above, it is shown that the experiments will be extremely complicated systems with many components. Many assay techniques will be required.

Assessment of the extent to which studies of neutrino properties with solar neutrinos are complementary to those with accelerator beams and the extent to which they duplicate them

Working group leaders: Shaevitz/Barger (neutrino oscillations) and **Bowles/Gonzalez-Garcia** (solar neutrinos)

Measurements of neutrino mixing and masses will require investigations using both solar and Earth-based neutrino beams (reactors or accelerators). The early goals will be to test our understanding of the phenomena, restrict the oscillation parameters and see if further investigations have access to CP violation effects in the neutrino sector.

At present we have three pieces of evidence for neutrino flavour conversion: the solar neutrino deficit, the atmospheric neutrino anomaly, and the LSND result. While atmospheric and LSND data are difficult to accomodate within scenarios other than neutrino oscillations, solar neutrinos may still be well explained in the context of alternative mechanisms. Thus, first it will be imperative to show that the deficit in solar neutrinos are due to neutrino oscillations. This will be solved by KamLAND reactor experiment and/or future solar neutrino experiments. Long baseline (LBL) accelerator experiments have no role in this.

If the three pieces of evidence are due to oscillations they point out towards oscillations with hierarchical mass square differences. For solar neutrinos, there are several ranges of $\Delta m^2_{\rm solar}$ still allowed within the present data analysis: Large Mixing Angle (LMA) (with $2 \times 10^{-5}{\rm eV}^2 < \Delta m^2_{\rm solar} < 2 \times 10^{-4}$ eV^2), LOW (with $\Delta m^2_{\rm solar} < 10^{-7}$ eV^2) or Vacuum solutions (with $\Delta m^2_{\rm solar} < 10^{-9}$ eV^2). Present global analyses prefer the LMA solution at greater than 99% C.L. For any of these solutions $\Delta m^2_{\rm solar}$ is much smaller than any of the other relevant mass differences.

It is this hierarchy between the mass differences relevant to solar and to atmospheric (and/or LSND) oscillations which makes the solar neutrino and accelerator based experiments target different pieces of the puzzle. After putting together all the existing data, one finds out that solar neutrinos are not quantitatively affected by oscillations with the mass differences and mixing angles relevant to atmospheric (and LSND) oscillations. These, on the other hand, can be precisely tested at LBL accelerator experiments studying $\nu_\mu \to \nu_\mu$ oscillations. Accelerator experiments may also probe the sign of $\Delta m^2_{\rm ATM}$, which, again, does not affect solar neutrino oscillations. (See the Executive Committee summary on neutrino oscillations.)

Conversely LBL accelerator experiments cannot provide any precise measurements of $\Delta m^2_{\rm solar}$ and $\theta_{\rm solar}$:

(i) For LOW and Vacuum solutions , the $\Delta m^2_{\rm solar}$ oscillations are totally inaccessible to Earth-based beam experiments even at the subdominant level.

(ii) For LMA (presently the favoured solution by the solar neutrino analysis) the KamLAND reactor experiment in Japan will provide Earth-beam based precise measurements of $\Delta m^2_{\rm solar}$ and $\theta_{\rm solar}$. Further precision on the determination of $\theta_{\rm solar}$ can be obtained with future solar neutrino experiments. (See the Executive Committee summary on solar neutrinos). In this case there will be a subdominant effect of $\Delta m^2_{\rm solar}$ oscillations at LBL accelerator experiments but no precision on the determination of $\Delta m^2_{\rm solar}$ and $\theta_{\rm solar}$ will be attainable. However in this case LBL accelerator experiments will be able to test the possibility of CP because they will be able to measure the product $\Delta m^2_{\rm solar} \sin^2 2\theta_{\rm solar}$, the mixing angle $\theta_{\rm CHOOZ}$, and the CP phase (provided that $\theta_{\rm CHOOZ}$ that governs $\nu_\mu \to \nu_e$ oscillations is not too small).

Summarizing, $\Delta m^2_{\rm solar}$ and $\theta_{\rm solar}$ can only be precisely measured at KamLAND and/or future solar neutrino experiments. $\Delta m^2_{\rm ATM}$ and $\theta_{\rm ATM}$ can only be precisely measured at LBL accelerator experiements. With these parameterers well determined, $\theta_{\rm CHOOZ}$ and the CP phase can be measured in LBL accelerator experiments.

We conclude that solar and accelerator studies of neutrino properties are highly complementary and that in none of the possible scenarios there is any duplication.

Solar Neutrinos / Stellar Processes Working Group Executive Summary*

Working Group Leaders: Thomas Bowles (tjb@lanl.gov); Concha Gonzalez-Garcia (Concepcion.Gonzalez-Garcia@cern.ch), Michael Wiescher (mwiesche@darwin.helios.nd.edu)

Introduction

The field of solar neutrino research has provided significant new information on the properties of neutrinos: in particular, the Sudbury Neutrino Observatory (SNO) has recently produced a model-independent demonstration that solar neutrinos undergo flavor transformation. It is clear that solar neutrinos allow insight into the ν sector as well as providing a probe of stellar processes. Indeed, these two activities are strongly coupled and both are required in any study of ν or stellar properties. It is clear this field offers well-defined opportunities to further extend our knowledge of the properties of neutrinos and for processes that are of primary importance in solar fusion and supernova explosions.

Importance of Future Solar Neutrino Experiments

For the foreseeable future, solar neutrinos will provide the only intense source of ν_e. The primary goal of future solar neutrino experiments will be to directly detect the low-energy part of the ν spectrum in real time, allowing for an independent measurement of the dominant flux of solar neutrinos - the p-p neutrinos. Such experiments will also provide a measurement of the ν fluxes from the ^{7}Be reaction and the CNO cycle. These measurements will allow for: (i) a direct test of the Standard Solar Model (SSM) and (ii) an improvement in our understanding of the properties of neutrinos.

A Direct Test of the SSM

Solar ν experiments (coupled with an understanding of ν properties) provide a stringent test of the SSM. For instance, as the fusion reactions that produce the different sources of neutrinos have different radial distributions, a full set of solar neutrino measurements allows one to probe the radial temperature dependence of the Sun. At present, the Ga, Cl, SuperKamiokande, and SNO experiments provide the following 1-σ uncertainties in the fluxes: $\delta f(\text{p-p}) = 18\%$, $\delta f(^7\text{Be}) \approx 35\%$, and $\delta f(^8\text{B}) = 13\%$, with the uncertainties in the p-p and ^{7}Be fluxes strongly correlated. In the near future, one can expect that with improved Ga, SNO, KamLAND, and Borexino results, one can achieve the following 1-σ uncertainties: $\delta f(\text{p-p}) = 12\%$, $\delta f(^7\text{Be}) = 8\%$, and $\delta f(^8\text{B}) = 8\%$.

The need for improving the accuracy of the measured fluxes can be questioned as the p-p flux is claimed to be known to 1% accuracy from the SSM. In fact, this quoted uncertainty is not SSM independent and the p-p flux is not completely determined by the solar luminosity. On the contrary, the predicted value of the p-p flux strongly depends on details of the solar model that, in particular, determine the ratio of the rates of the two primary ways of terminating the p-p fusion chain. The direct measurement of the p-p and ^{7}Be fluxes will allow us to test the SSM prediction for this ratio. This is a critical probe of solar fusion. Thus, in order *to provide a much more sensitive test of the SSM (at the % level), precision measurements of the total flux of the low-energy p-p and ^{7}Be neutrinos are required.*

Improving Our Understanding of the Properties of Neutrinos

Solar ν experiments that detect the charged-current (CC) interactions of ν_e measure the product of the solar flux times the survival probability for ν_e. Experiments detecting the electron scattering (ES) of ν_e measure, in addition, a contribution from the neutral current (NC) interaction of all ν active flavors, which is dependent on the conversion probability from ν_e to ν_μ □□□ ν_τ. The implication of these observations depends on the particle physics scenario considered for flavor mixing.

a) Current status of our knowledge

All of the data presently available provide us with the following picture: 1) the high-energy ^{8}B neutrinos have a large non-ν_e component, 2) the survival probability for $E_\nu > 5$ MeV is essentially independent of energy, and 3) the survival probability increases at low energies (p-p and ^{7}Be neutrinos).

b) Assuming 3 neutrinos generations and CPT is conserved

Under this hypothesis, solar ν experiments that measure CC and/or ES can independently determine the flux of solar neutrinos and the survival probability of ν_e. This in turn determines the conversion probability into other active flavors by unitarity. Thus, experiments detecting the low-energy part of the solar neutrino spectrum will be able to determine the relevant ν_e survival probability at low energies.

The observations to date can be explained under one of the following three hypotheses: mass-induced flavor oscillations, flavor-changing neutral currents (FCNC), or resonant spin-flavor flip conversion (RSFF). If FCNC or RSFF account for the observed flavor transformation, future solar neutrino experiments are the best (and possibly only) means of probing this new physics. The effective survival probabilty for p-p neutrinos for these two scenarios differ by more than 10% and therefore the measurement of the p-p rate will discriminate between these two possibilities.

If active oscillations are the source of the flavor conversion, then the Large Mixing Angle (LMA) solution is highly favored, but the LOW and VACuum solutions cannot be completely precluded. We should soon know from the KamLAND and Borexino experiments if flavor oscillations are the explanation for the solar neutrino results. Of course, the possibility exists that KamLAND and Borexino may not observe effects consistent with flavor oscillations. In that case, it will certainly be essential to extend solar neutrino studies to lower energies in order to investigate the origin of the observed flavor oscillations as discussed above.

Assuming three active neutrino flavors (to accommodate the solar and atmospheric data), the mass states can always be labeled in the form that solar neutrinos are dominated by the mixing of the neutrino eigenstates ν_1 and ν_2. Thus, solar neutrino experiments are a primary source of information on δm_{12}^2 and θ_{12}. At this point, the best-fit LMA solution has $\delta m_{12}^2 \approx 6 \times 10^{-5}$ eV^2 and $\theta_{12} \approx 32°$. The uncertainties at the 90% C.L. allow $3 \times 10^{-5} < \delta m_{12}^2 < 2 \times 10^{-4}$ eV^2 and $26° < \theta_{12} < 36°$. KamLAND is expected to be able to define the allowed δm^2 range to 10-30% accuracy (worsening rapidly for higher values of δm^2). However, it will only improve our knowledge of the mixing angle slightly as their ultimate accuracy on the mixing angle is limited by their knowledge of the overall flux normalization. Similarly, if the LMA solution is the correct one, Borexino will provide information that is important for the neutrino sector and astrophysics, but it will not improve our knowledge of the mixing angle.

Future solar neutrino experiments that are sensitive to the low-energy p-p neutrinos provide the best prospect for improving our knowledge of θ_{12}. In order to achieve a sensitivity comparable to that projected for KamLAND, one needs to measure the p-p flux with the same accuracy as KamLAND expects for their overall flux normalization (which may range between 3% and 10%). In order to be comparable to the existing uncertainty in θ_{12} set by all available solar ν data, one needs to achieve an accuracy of 3%. This is no doubt a challenging proposition, yet a general goal of the next-generation solar neutrino experiments is to achieve 1% statistical accuracy. Since the ES cross section is known with great accuracy, one may be able to achieve comparable systematic uncertainties in ES experiments. The accuracy of CC experiments will likely be limited to a few percent by the uncertainty in the CC cross-section (which will be calibrated using intense artificial ν sources). An alternative approach (separating CC from NC in an ES measurement) may be able to overcome that limitation.

c) Allowing for the existence of sterile neutrinos in flavor oscillations

If a sterile neutrino exists, solar ν_e can oscillate into an admixture of active and sterile states. In this case, the determination of the oscillation probabilities requires one to compare the sum of CC and NC measurements with an accurately known flux of neutrinos. At present, this is done by comparing the measured CC + NC flux of ^{8}B neutrinos with the SSM prediction. Allowing the total ^{8}B solar ν flux to be greater than the SSM prediction results in a limit on a possible sterile component of ^{8}B neutrinos of ≈50% (90% CL). In the near future, if LMA is correct, KamLAND (together with the SNO CC and NC data) will provide a sensitivity of ≈ 13% for a sterile component of the ^{8}B neutrinos.

Improving substantially on the above limits for a sterile-ν admixture requires precision flux measurements of the low-energy (p-p and ^{7}Be) solar neutrinos. In order to do this in a SSM-independent way, one must extrapolate the suppression factor measured by KamLAND to lower energies and then measure the CC and NC p-p and ^{7}Be rates. In this case, the sensitivity is determined by the uncertainty in extrapolating the suppression factor (which is again limited by the overall normalization uncertainty in KamLAND) and the accuracies of the CC and NC p-p measurements. A model-dependent test can be made using the SSM prediction for the p-p flux and measuring the p-p CC and NC fluxes. Thus, one sees the need to push for accuracies in the CC and NC p-p fluxes in the percent range.

In any case, studies of possible sterile-ν admixtures in more general scenarios imply that the sterile component of the solar neutrino fluxes may be energy dependent. Thus, *low-energy solar neutrino experiments must necessarily be a part of any full study of sterile neutrinos.*

d) Allowing CPT violation with flavor oscillations

Since neutrinos have no intrinsic charge, they provide a unique probe for testing for a violation of CPT. If CPT is violated, the neutrino mass scales and mass differences will in general be different for ν and $\bar{\nu}$. Thus, a test for CPT violation in flavor oscillations must necessarily include both ν and $\bar{\nu}$ measurements. If KamLAND finds an oscillation signal, it will determine the oscillation probability for $\bar{\nu}$. Then, assuming that Borexino agrees with the expected LMA solution (if it does not, CPT violation will have been already been discovered), a *test of CPT* will need a determination of the ν_e survival probability with equivalent precision. This *requires a measurement of the p-p rate to accurately measure the neutrino oscillation parameters*. This will allow in some models a constraint on the source of CPT violation at a scale < 10^{-20} GeV, which can be compared with the present CPT test from the upper limit on the mass difference in the kaon system of <4.4 x 10^{-19} GeV.

e) Limits on a neutrino magnetic moment

If neutrinos have a magnetic moment, their interaction cross section for ES will be substantially modified due to the electromagnetic interaction. This will result in a distortion in the spectrum of the scattered electrons. This effect is larger at lower energies making a solar low-energy experiment an optimum place to search for this effect. At present, the strongest limit on neutrino magnetic moments is for $\mu(\nu_e) < 1.5 \times 10^{-10}$ Bohr magnetons. *Preliminary estimates indicate that the current limit could be improved by an order of magnitude in future solar ν experiments that measure the ES of p-p neutrinos.*

Comparison / Complementarity with Other Types of Oscillation Experiments

See separate document by the Working group leaders: Shaevitz/Barger (neutrino oscillations) and Bowles/Gonzalez-Garcia (solar neutrinos).

Supernovae

The physics of supernovae is rich and complex. Neutrinos are believed to be the primary driver for the explosion and provide the most sensitive probe of core collapse physics, including the explosion mechanism, proto neutron star cooling, quark matter, and black hole formation. Since the couplings of ν_e, $\bar{\nu}_e$, and ν_μ / ν_τ are different, the various flavors decouple at different temperatures and thus have characteristic energy distributions. This, coupled with the high densities in supernovae, leads to the possibility of flavor oscillations playing an important role in the supernova evolution. Studies of the ν arrival time, energy spectra, and flavor composition allow us to carry out ν mass measurements with a potential sensitivity of a few eV and to understand the ν mass hierarchy and flavor transformations. In addition, the ν_e and $\bar{\nu}_e$ play important roles in the nucleosynthesis reactions that occur in the supernova environment. The possibility of sterile neutrinos and flavor oscillations may play a critical role in the production of heavy elements in supernova. Finally, detection of the ν burst from a supernova provides a means to provide an early warning to the astronomy community, providing the opportunity to see first light from the supernova, an important ability in understanding supernova dynamics.

Solar ν detectors are also superb supernova detectors. With their low energy threshold, large mass, and low backgrounds, they are able to observe supernova at long times following the explosion. They *are able to identify the ν flavor and provide the only means of measuring the ν_e energy spectrum from a supernova.* In order to observe ≈100 inverse beta decay events (from ν_e and ν_e each) from a galactic supernova at 10 kpc requires detector masses of several hundred tons. Another potential reaction is ν-nucleus coherent scattering, which is primarily sensitive to higher energy ν_μ and ν_τ. This reaction provides spectral information and rates ranging from 1 event/ton for ^{4}He to 31 events/ton for Xe. Dedicated supernova detectors (such as LVD and the proposed Omnis detector) provide the long-term coverage required for supernova observation (≈ 1/30 yrs) and the ability to address important physics issues. The very large proton decay and long-baseline experiments (such as UNO and LANND) provide the opportunity to observe ES reactions with rates of 10^4-10^5 events, allowing detailed studies of supernova evolution and neutrino mixing effects and, for the first time, sensitivity to extragalactic supernovae.

Opportunity for an Underground Accelerator

The prediction of the SSM ν fluxes has been hampered by the uncertainties in the associated nuclear reaction rates. The uncertainties are even larger in charged-particle reactions that drive late stellar evolution and are responsible for neutron production in the s-process, which feeds the formation of heavy elements up to Pb. The experimental study of these reactions has been a major goal in nuclear astrophysics for the last three decades. *The installation of an accelerator laboratory at an underground (u/g) location, coupled with the utilization of recent accelerator, detector, and data handling technology could lead to a major breakthrough in our understanding of the formation of the elements.*

The LUNA accelerator at the Gran Sasso Laboratory has succeeded in making the first nuclear reaction measurements at stellar temperature conditions. However, LUNA is too limited in scope and size to maintain a successful nuclear astrophysics program beyond the measurement of pp-chain reactions. Thus, the US community proposes the development of a dedicated u/g accelerator facility with capabilities far beyond those available at LUNA. While recognizing the advantages of a cosmic ray-free environment for low cross section reaction studies, the US groups propose to complement the passive shielding conditions with the latest detector technology to allow active event identification and background reduction. This will improve the signal/background considerably by identifying and reducing beam-induced backgrounds. The implementation of new, commercially available accelerator technology will provide one to two orders of magnitude higher beam intensities.

The study of stellar He burning processes also requires substantially higher beam energies than those available at LUNA. The development of a high-intensity ECR source will allow the future application of inverse kinematics techniques for stellar reaction studies. A depth of 4000 mwe is required to suppress cosmic ray-induced neutrons. The laboratory needs at least 20w x 35d x 10h m, with an overhead crane, and expansion space should be planned for to allow for the installation of a recoil separator.

The proposal of such a facility requires careful study and preparation of the necessary experimental techniques. The simulation of u/g detection techniques will be performed in collaboration with the LUNA group and the development of active shielding and event-tracking techniques will be developed at US low-energy accelerator facilities. This program will require a few years of effort, and thus we anticipate that an u/g accelerator could be one of the first facilities installed at NUSL.

Facility Requirements

There are a number of experiments under active development in the US: for the CC reaction - Hybrid, LENS, and Moon; for ES - CLEAN and Heron; and for ES with separation into CC and NC - TPC. It is expected that at least two of these experiments will submit full proposals within the next two years. With the exception of TPC (which requests a depth of 2000 mwe), all of the experiments need depths of 3000-7000 mwe and all would benefit by being very deep.

The volumes required range from 4000 to 50,000 m^3. Electrical power requirements range from 200 to 1000 kW (for the accelerator). All need clean conditions and have extremely high radiopurity requirements. All of the experiments require underground storage space during construction (to reduce cosmogenic backgrounds) and several require underground fabrication (e.g., electroformed Cu) of components. The experiments present a number of significant safety concerns (e.g., large volumes of cryogens and scintillator, high pressures). It is clear that all of the experiments would substantially benefit from centralized services (e.g., Rn-free N_2) and a low-background counting facility.

Multiple-Use Capabilities of Solar Neutrino Detectors

The proposed experiments all have one feature in common: a low energy threshold. This allows the solar ν detectors to study a wide range of physics including $\beta\beta$ decay, dark matter, ν magnetic moment, supernovae, and geophysical neutrinos. For example, Moon is designed primarily as a $0\nu\ \beta\beta$ experiment with the capability to reach $m_\nu \approx 50$ meV and is also sensitive to the CC interaction of p-p and ^{7}Be neutrinos. The ES experiments are sensitive to recoil nuclei from WIMP interactions and have large (multi-ton) masses. How competitive they are depends on the WIMP mass and the backgrounds that can be achieved, which remain to be seen. The ES experiments can likely achieve a sensitivity to a ν magnetic moment of $\approx 10^{-11}$ Bohr magnetons. Both the CC and ES experiments would provide good sensitivity to a supernova with low energy thresholds and the ability to discriminate between ν_e, $\bar{\nu}_e$, □□□ ν_μ/ν_τ. The proposal that the Earth's core is fueled by a nuclear reactor can be tested using geographically separated low-energy $\bar{\nu}_e$ detectors, which is within the capabilities of some of the proposed CC detectors.

E&O Opportunities

Students, teachers, and the public find this area of physics to be very exciting. E&O efforts are included from "the ground up" in the proposed research. Many of the experiments are small to medium in scale and the physics is interesting and accessible to a broad range of students. The research allows students and teachers to participate in multi-disciplinary research that includes atomic, molecular, nuclear, and particle physics, and astrophysics and cosmology. The experiments employ a wide range of state-of-the art technology that in turn makes the project very attractive for undergraduate and graduate student involvement, providing a very real exposure to forefront physics

Conclusions

- Future solar neutrino experiments will provide a stringent test of the Standard Solar Model.
- Future progress in understanding the complete neutrino mixing matrix requires an active program in low-energy solar neutrino experiments.
- Future solar neutrino research requires a deep (>4000 mwe) and dedicated underground laboratory.
- An underground accelerator facility would allow significant progress in our understanding of stellar processes and should be included in the plans for NUSL.
- This research program would benefit significantly from the centralized infrastructure at NUSL.

** This report incorporates input from the 70 participants who registered for this working group. In addition, the report findings were coordinated with the leaders of the double beta decay, dark matter, long-baseline, and low-level counting working groups.*

Proton Decay group summary statement

NESS02 September 21, 2002

Theoretical Motivation

While current experiments show that the proton lifetime exceeds about 10^{33} years, its ultimate stability has been questioned since the early 1970's in the context of theoretical attempts to arrive at a unified picture of the fundamental particles – the quarks and leptons – and of their three forces: the strong, electromagnetic and weak. These attempts of unification, commonly referred to as "Grand Unification", have turned out to be supported empirically by the dramatic meeting of the strengths of the three forces, that is found to occur at high energies in the context of so-called "Supersymmetry", as well as by the magnitude of neutrino masses that is suggested by the discovery of atmospheric and solar neutrino oscillations. One of the most crucial and generic predictions of grand unification, however, is that the proton must ultimately decay into leptonic matter such as a positron and a meson, revealing quark-lepton unity.

Certain early versions of grand unification based on the so-called SU(5) and minimal supersymmetric SU(5) models predict relatively short lifetimes for the proton ranging from 10^{28} to 10^{32} years, in the $e^+ \pi^0$ and νK^+ respectively. These predictions have been excluded by the IMB/Kamiokande and Super-Kamiokande experiments. A class of well-motivated theories of grand unification, based on the symmetry of SO(10) and Supersymmetry, which have the virtue that they successfully describe the masses and mixings of all quarks and leptons including neutrinos, and which also explain the origin of the excess of matter over anti-matter through a process called "leptogenesis", provide a conservative (theoretical) upper limit on the proton lifetime which is within a factor of ten of the current lower limit. This makes the discovery potential for proton decay in a next-generation rather high.

From a broader viewpoint, proton decay, if found, would provide us with a unique window to view physics at truly short distances – less than 10^{-30} cm., corresponding to energies greater than 10^{16} GeV – a feature than cannot be achieved by any other means. It would provide the missing link of grand unification. Last, but not least, it would help ascertain our ideas about the origin of an excess of matter over anti-matter that is crucial to the origin of life itself. In this sense, and given that the predictions of a well-motivated class of grand unified theories for proton lifetime are not far above the current limit, the need for an improved search for proton decay through a next-generation detector seems compelling. The theoretical guidance provided by a class of promising models, including those based on Supersymmetric SO(10), flipped SU(5) and string-derived SU(2)xSU(2)xSU(4) symmetries, points especially towards the need for improved searches for proton decaying into νK^+ and $e^+\pi^0$ modes with lifetimes less than about 2×10^{34} and 10^{35} years respectively. Should proton decay be discovered in these modes, valuable insight would be gained by searches for other related modes including $\mu^+ \pi^0$ and μ^+K^0.

Current status of experimentation

The "classical" proton decay mode, $p \rightarrow e^+\pi^0$, can be efficiently detected with low background. At present, the best limit on this mode ($\tau/\beta > 5.7\times10^{33}$ yr, 90% CL) comes from a 92 kton-yr exposure Super-Kamiokande. The detection efficiency of 44% is dominated by final-state π^0 absorption or charge-exchange in the nucleus, and the expected background is 2.2 events/Mton-yr.

The mode $p \rightarrow \nu K^+$, is experimentally more difficult in water Cherenkov detectors due to the unobservable neutrino. The present limit from Super-Kamiokande is the result of combining several channels, the most sensitive of which is $K^+ \rightarrow \mu^+\nu$ accompanied by a de-excitation signature from the remnant ^{15}N nucleus. Monte Carlo studies suggest that this mode should remain background free for the foreseeable future. The present limit on this mode is $\tau/\beta > 2.0\times10^{33}$ yr (90% CL).

Requirements for the next decade

Since the lifetime of the nucleon is unknown, *a priori* (if one were to ignore theoretical guidance), and could range from just above present limits to many orders of magnitude greater, progress in this search must be measured logarithmically: increases in sensitivity by factors of a few are insufficient to motivate new experiments. Thus, continued progress in the search for nucleon decay inevitably requires much larger detectors. The efficiency for detection of the $e^+\pi^0$ mode is dominated by pion absorption effects in the nucleus, and cannot be improved significantly. An order of magnitude improvement in this mode can only be achieved by running Super-Kamiokande for an additional 30-40 more years, or by constructing an order of magnitude larger experiment.

The decay modes of the nucleon are also unknown, *a priori,* and produce quite different experimental signatures, so future detectors must be sensitive to most or all of the kinematically allowed channels. Moreover, the enormous mass and exposure required to improve significantly on existing limits (and the unknowable prospects for positive detection) underline the importance of any future experiment's ability to address other important physics questions while waiting for the proton to decay. Proton decay experiments have made fundamental contributions to neutrino physics and particle astrophysics in the past, and any future experiment must be prepared to do the same.

New facilities under consideration

A variety of technologies for discovery of nucleon decay have been discussed. Of these, water Cherenkov appears to be the only one capable of reaching lifetimes of 10^{35} years or greater. Cooperative, parallel studies of a future underground water Cherenkov proton decay experiment are underway in the U.S. and Japan. The proposed designs range from 450 kton (20 times Super-Kamiokande) to 1 Mton.

Other techniques, for instance liquid Argon or scintillation, have been discussed and may have significant efficiency advantages for certain modes that are dominant in a certain broad class of SUSY theories. Liquid Argon feasibility will be demonstrated in the near future with the operation of a 3000-ton ICARUS detector. If expectations are correct, it should be able to equal the sensitivity of Super-Kamiokande in the $p \rightarrow \nu K^+$ mode. The liquid scintillator approach is presently being explored with the 1kt

KamLAND experiment. It should also have enhanced sensitivity to this mode by directly observing the K^+ by dE/dx and observing the subsequent $K+ \rightarrow \mu^+$ decay.

Performance and feasibility

Detailed Monte Carlo studies, including full reconstruction of simulated data, indicate that the water detectors could reach the goal of an order of magnitude improvement on anticipated nucleon decay limits from Super-Kamiokande. With sufficient exposure, clear discovery of nucleon decay into $e^+\pi^0$ would be possible even at lifetimes of (few) $\times 10^{35}$ years where present analyses would be background-limited, by tightening the selection criteria. For instance, with a detection efficiency of 18%, the expected background is only 0.15 events/Mton-yr, ensuring a signal:noise of 4:1 even for a proton lifetime of 10^{35} years. Either proposed water Cherenkov detector would provide a decisive test of super-symmetric SO(10) grand unified theory by reaching a sensitivity of a (few) x 10^{34} years for the νK^+ mode.

A much smaller liquid argon or scintillation detector could do particularly well on the mode νK^+ as the efficiency could be as much as 10 times larger than that in the water Cherenkov detectors due to the extraordinary bubble chamber-like pattern recognition capabilities. Due to this, a single observed event could be powerful evidence for a discovery. The $e^+\pi^0$ mode however would be limited by the smaller size of these detectors.

A detector with mass O(1 Mton) would also be a powerful tool for studying neutrino physics. Thanks to the larger dimensions of the detector, higher energy neutrino-induced muons can be fully contained and their energy can be measured. Using the atmospheric neutrino flux, the distinctive oscillatory pattern as a function of L/E could be directly observed. A large proton decay detector would also be the ideal distant detector for a long-baseline oscillation experiment; several studies indicate sensitivity to $\sin^2 2\theta_{13}$ at about the 10^{-3} level, and sensitivity to leptonic CP violation in certain scenarios.

The working group also heard a presentation on n-nbar oscillation. While this is not one of the favorite predictions of conventional SUSY grand unification, this process, taking place in the nuclear potential, can reach an equivalent sensitivity to Baryon non-conservation of 10^{35} years.

Depth requirements

Most of the decay modes that were searched for in the first generation detectors required only modest depth. IMB operated successfully at a depth of 2000 feet. The proposed Homestake or San Jacinto depth (about 6500 mwe) would reduce the muon background by about a factor of 100 with respect to Super-K and certainly help in the observation of modes with a low energy component or those influenced by fast neutron background. As an example of this, the mode $n \rightarrow \nu\nu\nu$ can be search for by observing the de-excitation of the residual nucleus. This is difficult with a background of fast-neutron induced low energy background events.

Possible improvements in institutional support

To carry forward the search for nucleon decay – the “smoking gun” of grand unification will require a renewed commitment to this essential physics on the part of the United States, ideally as part of a global effort. It may not be practical to construct and operate more than one detector of the required size, and research groups in Europe, Japan and the United States are fully cognizant of the need to work together (and indeed are already doing so). The first large proton decay experiment – IMB – was an American innovation, and others soon recognized the power of the water Cherenkov technique. Despite the success of IMB and its cousin Kamiokande, the present generation experiment was built in Japan with only a token U.S. investment in its construction. Even so, nearly 100 U.S. physicists have worked on the project at one time or another, and it continues to produce superb and exciting results. There is every reason to expect that the next generation proton decay experiment will accumulate an equally impressive list of accomplishments, if support commensurate with its physics potential is forthcoming.

R&D towards more efficient and economical photo-detection – both improved conventional photo-multiplier tubes and more novel technologies – while not required to build the next large detector, could reduce its cost and increase its physics reach considerably. This R&D should be strongly supported, since they will also benefit a host of other research efforts.

Finally, the search for proton decay is only one of many particle physics and astrophysics activities requiring extensive, modern underground infrastructure. A national underground laboratory would greatly facilitate not only proton decay, but also a whole spectrum of large and small experiments now being planned or discussed. Such a laboratory would undoubtedly achieve tremendous economies, by providing a single, centralized infrastructure for many experiments, each of which would otherwise be forced to duplicate it themselves. While the site requirements for proton decay are more modest than those of other low-background experiments, a modern, purpose-built facility, designed to facilitate construction and operations would provide the ideal venue.